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Effects on winter wheat: A comparison of five models.
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5.7 Effects on winter wheat: A comparison of five models

5.7.1 Background

Differences in modelling approach may cause significant differences in output from crop growth simulation models. This is an important consideration in the context of climate change research as the tendency has been to apply individual crop models using scenarios constructed from a range of GCMs. This provides a useful assessment of the uncertainty surrounding possible future climates. However, uncertainties arising from different modelling approaches also need to be quantified.

Crop models are developed for widely varying environmental conditions and for different objectives and, hence, emphasize different parts of the plant/soil/climate system. This leads to very different models which vary in their description of various processes, input requirements and sensitivities to environmental conditions. A truely mechanistic crop model should be able to reproduce experimental results for a range of environmental conditions. Such robust and reliable models are critical for predicting the response of agriculture to changing climatic conditions. However, the description of processes and the parameters in models are often highly related to their testing conditions and are less universal than expected.

Recently the performance of three wheat models was tested against observed crop data in New Zealand (Porter *et al.*, 1993). In this detailed analysis the time courses of absorbed radiation, total and grain dry matter production and other plant characteristics were compared. The study indicated where the models differed from reality or from each other and where the models might be improved.

In the Global Change and Terrestrial Ecosystems (GCTE) Focus 3 Wheat Network eight wheat models were run for two climate data sets, one from Minnesota, U.S.A. and one from the Netherlands. The wheat models differed greatly in complexity, structure and parameterisation conditions (GCTE, 1994). Model results differed to a surprising degree. A detailed growth analysis was not undertaken and field data sets were not used for comparison. This made it difficult to trace the cause of the large differences because of the complexity and many feedbacks in the models. The conclusion from this modelling exercise was that crop growth models are not yet at a stage of development where they can be used for strongly different environmental conditions. They need at least a calibration of their parameter set against detailed field experiments before they can be applied (Goudriaan, 1994).

In this study a thorough comparison of the performance of five wheat models has been carried out for different agroclimatic conditions in Europe. Models have been compared for both current climatic conditions and a range of possible future climates. The approach was consistent with that of the GCTE Wheat Network but was more extensive in order to avoid some of the problems previously mentioned. A complementary activity within the GCTE Wheat Network has recently started which includes a comparison of wheat models on the basis of their process descriptions (Goudriaan and Porter, pers. comm., 1995). Such detailed analyses of similarities and differences in calculation routines in different wheat models will be extended in the future.

A number of possible future climates, climate change scenarios, were applied to the wheat models. These included both changes in the mean and variability of climatic variables. The majority of climate change impact assessments have used only average changes in climate and have kept the variability of weather parameters unchanged (Santer *et al.*, 1990; Giorgi and Mearns, 1991; Kenny *et al.*, 1993). However, information about changes in climatic variability are also required to build a complete picture of likely impact distributions. The relative importance of changes in climatic variability compared with changes in mean values has been investigated in sensitivity analyses by Semenov and Porter (1995). This study clearly demonstrates that plausible changes in the variability of temperature or precipitation can sometimes have larger negative effects on average yield and yield stability than changes in means. Moreover, simultaneous changes in the mean and variance of temperature can amplify the decrease in yield and thus the overall effect cannot be viewed as a simple arithmetic sum of the individual decreases. These effects have been assessed in this study, using climate data sets generated with a stochastic weather generator (see Section 2.4 for more information). There have been other attempts to incorporate changes in climatic variability into climatic scenarios (Mearns *et al.*, 1992). This approach however, using a weather generator instead of historical weather data, in conjunction with a crop simulation model, appeared to be methodologically more consistent (Semenov and Porter, 1995).

5.7.2 Methodology for model comparison

Five models (AFRCWHEAT, CERES-Wheat, NWHEAT, SIRIUS and SOILN-Wheat) were evaluated. The complexity and many feedbacks included in these models meant that it was very difficult to explain the results and sensitivities of different models on the basis of differences in model structure, source code and input data. Hence, the model comparison was based mainly on results. There were four main steps to the comparison. Firstly, models were calibrated and validated against field data sets. Secondly, the sensitivity of wheat growth and development to independent changes in temperature, precipitation and atmospheric CO_2 concentration was investigated. Thirdly, models were run for a number of possible future climatic conditions, using the climate change scenarios described in Chapter 2. Fourthly, models were run for the same climate data sets used in the sensitivity and scenario analyses, but with changed variability in rainfall distribution and temperature. All analyses have been conducted for two European sites, Rothamsted, U.K. and Sevilla, Spain.

The following crop characteristics are produced as output by most of the models and were used to characterise the sensitivities of, and the differences between, the models:

- day of year of emergence, anthesis and maturity: [DE, DA, DM];
- grain yield and total above-ground biomass as dry matter (1000 kg DM/ha): [GR, TB];
- maximum green leaf area index (m^2 leaf/m^2 ground surface): [LAM];
- cumulative evapotranspiration from emergence to maturity (mm): [ET];
- water use efficiency, i.e. total above-ground biomass / cumulative evapotranspiration (g DM/kg H_2O) [WUE];
- cumulative intercepted photosynthetically active radiation (PAR) from emergence to maturity (MJ/m^2): [RI];
- radiation use efficiency, i.e. total above-ground biomass / cumulative intercepted PAR (g DM/MJ PAR): [RUE];
- harvest index, i.e. grain yield / total above-ground biomass (kg DM/kg DM) : [HI];
- amount of nitrogen in total above-ground biomass (kg N/ha): [NB];
- nitrogen use efficiency, i.e. total above-ground biomass / amount of nitrogen in total above-ground biomass (kg DM/kg N): [NUE].

5.7.3 Model description

A short description of the main routines of each wheat model is given. For more information on the main plant, soil and weather processes incorporated in these models, their input requirements and output produced, see the literature mentioned in the various model descriptions and the model database of the GCTE Wheat Network (GCTE, 1994).

5.7.3.1 *AFRCWHEAT 3S model*

AFRCWHEAT is a complex model of the growth and development of a wheat crop that describes its phenological development, dry matter production and partitioning in response to the environment using a daily timestep (Porter, 1984, 1993; Weir *et al.*, 1984). The model includes subroutines which describe crop transpiration and soil evaporation, the movement of water and nitrogen in the soil profile and their uptake and effects on growth.

Crop phenology

Timing of phenological stages follows calculation of a succession of phases whose thermal duration is modified by the crop's response to daylength and vernalization. Phenology sets the time frame for other developmental processes such as leaf production and tillering (Porter, 1984).

Crop growth

Production of dry matter depends mainly on the rate of photosynthesis. The photosynthesis routine describes the response of carbon fixation by the canopy to both CO_2 concentration and photosynthetically active radiation (PAR) absorbed by the leaf canopy. The partitioning of dry matter between leaves, stems, roots, ears and grains is determined by partitioning factors whose values vary with phenological stage. As the crop approaches the start date of grain filling, some dry matter is diverted from stems and leaves to a labile pool that is potentially available to the grains. During grain-filling all new dry matter goes to the grains, and the labile pool can also contribute to grain mass at a temperature-determined rate. Leaf production is calculated as a function of temperature, modified by the rate of change of daylength at emergence. The upper limit to leaf expansion is set by temperature and the availability of assimilate, water and nitrogen determines whether or not this maximum is reached.

Water balance

Simulation of soil water movement is based on the Solute Leaching Intermediate Model (SLIM) (Addiscot, 1977; Addiscot *et al.*,1986; Addiscot and Whitmore, 1987). The model simulates the daily movement of water through a layered soil and estimates how much is available for the crop. Water in each layer is treated as either mobile or retained. Excess water (when mobile water content is greater than the saturated level) is lost via rapid drainage to the bottom of the profile, bypassing the main body of the soil. The crop uptake of water is limited by availability in the rooting zone and the ability of the roots to absorb it. Evaporation from the soil and crop transpiration are calculated using the Penman equation. Crop transpiration is reduced when soil moisture is less than 65% of the available soil water in the rooting zone. A shortage of water is translated into two factors: SWDF1 hastens leaf senescence; SWDF2 reduces the leaf expansion rate and the life span of leaves, and increases specific leaf weight and the labile pool that is potentially available to the grains.

Nitrogen uptake and soil nitrogen

The SLIM model simulates the mineralization of organic nitrogen to ammonium and subsequent nitrification to nitrate as well as the distribution and movement of nitrogen throughout the soil profile. Added fertilizer is included in the top soil layer. The uptake of nitrogen by the crop is limited by its availability in the rooting zone and the ability of the roots to absorb it. The demand for nitrogen by the crop is calculated as the difference between current nitrogen concentration in the shoots and roots and their maximum value for the current development stage. Nitrogen shortage is translated into four factors: DEFN1 increases the death rate of tillers; DEFN2 reduces the leaf expansion rate; DEFN3 reduces the tiller production rate; DEFN4 increases leaf senescence, partitioning of dry matter to roots and the labile pool that is potentially available to the grains.

Direct effect of increases in atmospheric CO_2

In the model, increasing atmospheric CO_2 concentration increases both the maximum photosynthetic rate (Weir *et al.*, 1984) and the quantum yield (Gaastra, 1962; Goudriaan and van Laar, 1978).

5.7.3.2 *CERES-Wheat model*

CERES-Wheat describes phenological development and growth of a wheat crop in response to environmental factors (soil, climate and management) using a daily timestep (Godwin *et al.*, 1990; Ritchie and Otter, 1985). Modelled processes include phenological development, crop growth and dry matter partitioning among plant organs, extension growth of leaves and stems, senescence of leaves, and root system dynamics. The model includes subroutines to simulate water and nitrogen balances. This enables the effects of nitrogen deficiency and soil water deficit on biomass production and yield to be estimated.

Crop phenology

The primary variable influencing phasic development is temperature. The thermal time for each phase is modified by coefficients that characterise the response of different wheat genotypes. The timing of crop phenological stages can be calibrated by modifying coefficients that characterise vernalization (P1V), photoperiod response (P1D), duration of grain filling (P5) and phyllocron interval (PHINT) of a particular variety.

Crop growth

Potential dry matter production is a linear function of intercepted photosynthetically active radiation (PAR), modified by temperature. The percentage of incoming PAR intercepted by the canopy is an exponential function of leaf area index. Dry matter allocation is determined by partitioning factors that depend on the phenological stage and the degree of water stress. Final grain yield is the product of plant population density, grains per plant and grain weight. The number of grains per plant is a linear function of stem weight and coefficients that account for the variation between genotypes in the number of grains per ear (G1) and spike number (G3). The maximum grain growth rate is an input coefficient that depends on the wheat genotype (G2).

Water balance

Precipitation is a daily input. Runoff is a function of soil type, soil moisture and precipitation. Infiltration is equal to precipitation minus runoff and drainage occurs when soil moisture exceeds the water-holding capacity of the bottom soil layer. Potential transpiration is calculated using the Priestly-Taylor approach. Actual transpiration is modified by leaf area index, soil evaporation and soil water deficit. Actual evaporation is a function of potential evaporation, LAI and time as described by Ritchie (1972). Daily change in soil moisture is calculated from precipitation minus transpiration, evaporation, runoff and drainage.

Direct effect of increases in atmospheric CO_2.

The model has been modified to simulate changes in dry matter production and transpiration as a result of changes in atmospheric CO_2 concentration. These modifications have been based on information from the literature as described by Rosenzweig and Iglesias (1994).

5.7.3.3 *NWHEAT model*

NWHEAT simulates the growth of a wheat crop and its response to environmental conditions. The simulation of growth and water and nitrogen dynamics is carried out in timesteps of one day. The model comprises submodels that simulate crop growth, phenological development, nitrogen uptake by the crop, soil nitrogen dynamics and soil moisture dynamics. The principles underlying this model have been discussed by Groot and de Willigen (1991) and Groot and Spiertz (1991). The model has been described completely by Groot (1987, 1993).

Crop phenology

Phenological development depends on the ambient temperature and is modified to account for the effects of vernalization and photoperiod.

This description of crop development is based on the model described by Porter (1984) and Weir *et al.* (1984), but has been adapted for Dutch conditions on the basis of results from wheat trials described by Reinink *et al.* (1986). From anthesis, phenological development is determined only by ambient temperature.

Crop growth

Simulation of crop growth is based on the model described by Spitters *et al.* (1989). Gross assimilation of the canopy is calculated as a function of leaf area index, radiation distribution in the canopy and the photosynthesis-light response curve of individual leaves. Maintenance requirements for the different plant organs, calculated as a function of their weight and chemical composition (Penning de Vries, 1975), are subtracted from daily gross assimilation. The remaining assimilates are allocated to leaves, stems and roots depending on the phenological development of the crop. Allocated assimilates are converted to structural plant material by taking into account conversion losses. After anthesis no vegetative growth occurs and all assimilates and stem reserves are allocated to grains.

Water balance

The soil is treated as a multilayered system. For each layer, changes in soil moisture content are the result of infiltration, water losses as a result of soil evaporation and crop transpiration, and downward movement to the lower layer. If precipitation occurs, the first layer is filled to field capacity. Excess water drains to the next layer which is also filled to maximum field capacity. This procedure is repeated for the deeper layers as long as there is excess water. Upward movement of water, for example capillary rise from ground water, is not calculated by the model. Potential soil evaporation is calculated using the Penman approach (Frère and Popov, 1979) and potential crop transpiration by the Penman-Monteith approach (Smith, 1992). Maximum rates of evaporation and transpiration are calculated from potential rates by correction for the degree of light interception by the canopy. Actual evaporation becomes lower than the maximum if the soil moisture content in the top layer decreases, and actual transpiration is lowered if the moisture content in the root zone decreases. When actual transpiration is smaller than maximum transpiration, gross canopy assimilation is reduced proportionally.

Nitrogen uptake and soil nitrogen

Soil nitrogen supply depends on fertilizer nitrogen application, nitrogen in rainfall, decomposition of old (humus) and fresh organic matter (crop residues), crop nitrogen uptake and downward movement of nitrogen by leaching. Denitrification and ammonia volatilization are not taken into account. Decomposition, which is treated as a process with first-order kinetics, results in either mineralization or immobilization of nitrogen, depending on the C/N ratio of the substrate. Following the approach proposed by Burns (1974), water and mineral nitrogen entering a soil layer by leaching and mineralization are completely mixed with water and nitrogen already present. The resulting nitrogen concentration multiplied by the downward water flow, results in the downward transport of nitrogen. Before anthesis crop nitrogen demand is based on the concept of nitrogen deficiency of leaves, stems and roots. As long as the nitrogen content is below its maximum possible value, there will be a sink for nitrogen. The values used for the maximum nitrogen content decrease over time, dependent on the stage of crop development. The actual nitrogen uptake proceeds according to crop demand as long as the soil nitrogen supply is not limiting. After anthesis crop nitrogen may be translocated to the grains which lowers both the nitrogen content and photosynthetic capacity of vegetative tissue.

Direct effect of increase in atmospheric CO_2

This effect was incorporated in the model by increasing the maximum value (AMAX) and the initial angle of the CO_2 assimilation - light response curve of single leaves, by increasing the thickness of leaves, and by decreasing the stomatal conductance. These changes in model parameters were based on studies by Chaudhuri *et al.* (1990), Dijkstra *et al.* (1993), Goudriaan (1990), Goudriaan and Unsworth (1990) and on literature surveys on crop responses to CO_2

doubling by Cure (1985), Cure and Acock (1986) and Kimball (1983). Based on studies by Allen *et al.* (1990), Dijkstra *et al.* (1993) and Idso (1990), the positive effect of increasing CO_2 on AMAX is reduced when day temperatures drop below 20°C.

5.7.3.4 *SIRIUS model*

SIRIUS is a relatively simple wheat model using a daily timestep (Jamieson and Wilson, 1988; Jamieson, 1989). The new version of the model includes soil water and nitrogen submodels so that crop responses to water and nitrogen limitations can be studied (Jamieson *et al.*, 1995).

Crop phenology

The simulation of phenological development is based on leaf appearance and thermal time. Appearance of leaves depends on thermal time and leaf number. The final leaf number is determined by day length and vernalization. After appearance of the flag leaf ligule on the mainstem the rate of phenological development to anthesis and during grain filling is determined by thermal time only.

Crop growth

Leaf area index is determined by thermal time and phenological stage. It is modelled in four stages: an exponential increase with thermal time from emergence to an LAI of 5; a linear increase with thermal time from an LAI of 5 to 8.5; a constant maximum value of 8.5 until anthesis; and a decrease quadratically related to thermal time so that leaf area index reaches zero at the end of grain filling. The fraction of radiation intercepted by the canopy is calculated from Beer's law. Dry matter accumulation is calculated from intercepted radiation with a fixed value for the radiation-use efficiency. All new assimilates are allocated to the grains once grain growth starts. In addition, a pool of 20% of the amount of dry matter at anthesis is bled into the grain at a temperature determined rate.

Water balance

This submodel is based on the Solute Leaching Intermediate Model (SLIM) (Addiscott, 1977; Addiscott *et al.*, 1986) and the water balance model WATCROSS (Aslyng and Hansen, 1982). Precipitation is partly intercepted by the leaves, the remaining water reaches the soil surface and after infiltration water percolates downwards and is distributed between the soil layers. The model has multiple soil layers, each with their own water storage capacity. To calculate potential crop transpiration the Ritchie (1972) model is used. This model takes into account the main environmental factors (net radiation, temperature and vapour pressure deficit). To derive the actual transpiration, potential transpiration is reduced for incomplete ground cover and soil moisture deficit. Soil evaporation is calculated with either energy or diffusion limited equations, of which the lowest result is used (Tanner and Jury, 1976). The energy limited equation is equal to potential evapotranspiration multiplied by the fraction of incoming radiation received at the soil surface, and the diffusion limited equation is equal to a fixed constant for soil diffusion divided by the square root of the time since the last date the soil surface was completely wet.

Nitrogen uptake and soil nitrogen

The nitrogen submodel is very similar to the NITCROS model (Hansen and Aslyng, 1984). The processes which determine changes in soil inorganic nitrogen are fertilizer nitrogen application, soil mineralization, denitrification, leaching, microbial fixation and nitrogen uptake by the crop. Maximum nitrogen uptake is determined by dry matter production and maximum nitrogen concentration which is a function of the age of the crop. Actual nitrogen uptake depends on both maximum nitrogen uptake and the available amount of inorganic nitrogen in the soil.

Direct effect of increases in atmospheric CO_2

Radiation use efficiency is assumed to increase linearly with atmospheric CO_2 concentration and to become 30% higher with CO_2 doubling.

5.7.3.5 *SOILN model*

SOILN simulates biomass and nitrogen dynamics in a wheat crop and is an application of a general soil-plant model, SOILN-CROP (Eckersten and

Jansson, 1991; Eckersten *et al.*, 1994; Johnsson *et al.*, 1987). The soil can be divided in layers of different thickness. In this study, however, only one layer, the root zone, has been used, because the focus was on plant dynamics of the model and optimum soil water and nutrient status was assumed. The model has a time step of one day. Plant biomass and nitrogen dynamics are based on the relationship between carbon and nitrogen described by Eckersten and Slapokas (1990). This model concept originates from the idea that carbon input is strongly related both to energy input (de Wit, 1965) and to nitrogen input (Ingestad *et al.*, 1981).

Crop phenology

Dates of emergence, end of grain filling and maturity are calculated with a temperature-dependent function that has been taken from AFRCWHEAT. The start of grain filling depends both on temperature and daylength.

Crop growth

Maximum growth is proportional to the radiation intercepted by the canopy leaf area. This proportion decreases during grain filling. Actual growth is the maximum growth reduced by low air temperature and low leaf nitrogen concentration. The plant is divided in two pools for each type of function simulated by the model: one pool for biomass and one for nitrogen. Leaves fix carbon from the atmosphere and roots take up nitrogen from the soil. Stems are used for storage. During grain filling grains are additional storage organs that are supplied with assimilates from stems. The partitioning of assimilates to roots, leaves and stems is governed by two linear functions. The fraction partitioned to roots decreases as total plant biomass increases. The partitioning between leaves and stems depends on the leaf area development. This partitioning is determined by the leaf area to shoot biomass ratio which decreases with increasing shoot biomass. Leaf biomass is calculated from leaf area development and specific leaf area, and stem biomass is the remaining part of the shoot biomass. During grain filling biomass is allocated from stems to grains and stems receive assimilates from roots and leaves. Before old leaves die, their biomass and nitrogen is translocated to stems.

Nitrogen uptake and soil nitrogen

Nitrogen allocation in the crop is determined by biomass allocation and nitrogen concentration in plant tissue. Maximum nitrogen uptake is the sum of the maximum demands by the different plant organs. The demand equals the daily growth multiplied by the maximum nitrogen concentration of the tissue concerned. Actual nitrogen uptake is the lower value of the demand and the amount of nitrogen available in the soil. This available amount is a fraction of the total mineral nitrogen in the root zone. The amount of mineral nitrogen depends on the rate of decomposition of soil organic matter which is a function of temperature and the C/N ratio of soil organic matter.

Direct effect of increases in atmospheric CO_2

This effect is not included in the model. For comparison with results from the other models it was assumed that biomass production increases by 30% with doubling of atmospheric CO_2.

5.7.4 Model calibration and validation

The ability of each model to reproduce observed data was tested for two sites, Rothamsted, U.K. and Sevilla, Spain. For each site two sets of experimental data were required, one set for model calibration and one set for model validation. The models were calibrated for a single variety at each site to overcome differences in parameterisation conditions between models.

Models were initially run for potential production, ie. assuming no limitations to growth from water or nitrogen availability. Thereafter, models were run for water-limited production where crop growth can be limited by the water supply from precipitation and soil storage.

Calibration was conducted in three steps:

(i) phenological development was calibrated such that modelled dates of emergence, anthesis and maturity were within the experimental error of the observed data;

(ii) simulated maximum green leaf area index was made (as much as possible) identical to observed data;
(iii) simulated biomass and yield were made (as much as possible) identical to the observed data for both potential and the water-limited production.

In both the calibration and validation exercise the models produced output every 10 days from sowing to the end of the growing season. To validate model performance, outputs were compared with both the outputs of the other models and with the experimental data.

5.7.4.1 *Rothamsted*

Data from two experiments, each using the winter wheat variety Avalon, were used for model calibration and validation. The experiments at the IACR-Rothamsted Experimental station investigated the interactive effects of water and nitrogen on crop growth. In this analysis only the results from experiments with large fertilizer-N application have been used. In the experiment used for calibration (Brimstone experiment 1985/86), sown on 10 October 1985, the crop was either fully irrigated (+I) or covered by a rain shelter (-I) from 29 April 1986 until maturity. In the experiment used for validation (Stackyard experiment 1984/85), sown on 5 October 1984, the crop was either growing on a soil maintained to within 25 mm of field capacity by irrigation (+I) or was covered by a rain shelter from 17 April 1985 (-I). Further details on the Brimstone experiments in 1985/86 are given by Weir (1988) and about the Stackyard experiments in 1984/85 by Barraclough *et al.* (1989). Porter (1993) also provides information on these experiments and tests the ability of the AFRCWHEAT model to simulate observed crop growth.

The initial and maximum amounts of available water assumed in all model runs were based on data from J.R. Porter (pers. comm., 1994). Historical sets of weather data were used. As only results from the experiments with large fertilizer N application have been used, it was assumed that N supply was not a limiting factor for crop growth and N uptake in the model runs.

Calibration

An overview of model results and the observed data for the calibration year (1985/86) is given in Table 5.7.1. All results except date of emergence (DE), date of anthesis (DA) and maximum green leaf area index (LAM) are given for the date of maturity. Note that the observed data are mean results from the experiments and the variation in experimental results was not taken into account in these analyses.

Rates of phenological development were calibrated well in most models, resulting in dates of anthesis (DA) and maturity (DM) identical to those observed (Table 5.7.1). Only SIRIUS and SOILN calculated a date of maturity that was too early. The calibration of maximum green leaf area index (LAM) was not as successful as phenology. AFRCWHEAT and SOILN did quite well, but CERES and NWHEAT calculated too low a value. In the SIRIUS model LAM was fixed at 8.5 which was greater than that observed in both the irrigated and water-limited experiments.

The simulated values for total above-ground biomass (TB) and grain yield (GR) were calibrated fairly well in the irrigated trial (Table 5.7.1). Only SIRIUS calculated rather low values for GR. In the water-limited trials (with rain shelter) the reduction of TB by water shortage was reproduced well by CERES and NWHEAT, but the reduction was overestimated by AFRCWHEAT and underestimated by SIRIUS. These over or underestimations were not due to model characteristics but were caused by the input value for soil water storage.

Identical values for harvest index (HI) were observed in both the irrigated and water-limited experiments, although crop growth in the water-limited trials was severely reduced by water stress at the end of the growing season. AFRCWHEAT calculated an identical HI for irrigated and water-limited situations, but CERES, NWHEAT and SIRIUS calculated much lower values in the water-limited situation, due to insufficient redistribution of assimilates to the grains.

Table 5.7.1 Plant characteristics as observed in the Brimstone wheat trials (fully irrigated (+I) or with rain shelter from 29 April (-I)) in 1985/86 at the IACR-Rothamsted Experimental station and as simulated by the different models.

	DE	DA	DM	GR	TB	HI	ET[1]	WUE[1]	RI	RUE	LAM	NB	NUE[2]
Observed +I	-	171	218	9.30	19.22	0.48	326	5.61	-	-	6.83	257	74.8
AFRCWHEAT +I	295	170	219	9.11	19.77	0.46	280	6.73	723	2.73	7.42	202	97.9
CERES Wheat +I	296	171	218	9.27	18.56	0.50	317	5.30	-	-	4.87	244	76.0
NWHEAT +I	295	171	218	9.80	19.56	0.50	319	5.99	720	2.72	4.70	267	73.2
SIRIUS +I	296	171	210	8.17	19.28	0.42	264	5.68	-	2.2	8.50	-	-
SOILN +I	295	-	208	9.04	18.39	0.49	-	-	773	2.38	6.86	221	83.2
Observed -I	-	168	218	7.51	15.70	0.48	219	6.48	-	-	6.28	196	80.1
AFRCWHEAT -I	295	170	219	6.06	13.55	0.45	167	7.56	545	2.49	5.98	139	97.5
CERES WHEAT -I	296	171	218	6.42	15.67	0.41	246	5.65	-	-	4.73	232	67.6
NWHEAT -I	295	171	218	6.07	15.34	0.40	220	6.79	688	2.23	4.49	186	82.6
SIRIUS -I	296	171	210	7.86	19.07	0.41	251	5.90	-	2.2	8.50	-	-

[1] Evapotranspiration and water use efficiency from day 110 to maturity.
[2] For the meaning of the abbreviations see Section 5.7.2.

Observed values for cumulative evapotranspiration (ET) were for the period from day 110 to the date of maturity (Table 5.7.1). In the irrigated situation simulated results from CERES and NWHEAT were almost identical to observed ET, whilst AFRCWHEAT and SIRIUS gave too low values. This resulted in a high water use efficiency (WUE) in the AFRCWHEAT run, but not in the SIRIUS run. This can be explained by the large amount of biomass at day 110 in the SIRIUS run, which resulted in a relatively small increase in biomass from that day until the date of maturity (Figure 5.7.1). In the water-limited runs the estimated soil water supply varied from relatively low in AFRCWHEAT to fairly high in CERES and SIRIUS which strongly influenced the water losses by ET. WUE is higher in the water-limited than in the irrigated situation. This can be explained by lower losses through soil evaporation in the water-limited situation.

AFRCWHEAT and NWHEAT calculated similar values for cumulative intercepted photosynthetically active radiation (RI) and radiation use efficiency (RUE) in the irrigated situation. No experimental data were available for these variables. Lower values of RUE were calculated by the SIRIUS and SOILN models. Simulated RUE decreased in the water-limited, compared to the irrigated, situation.

Observed values of nitrogen content in above-ground biomass (NB) and nitrogen use efficiency (NUE) were simulated reasonably well by CERES and NWHEAT for the irrigated situation (Table 5.7.1). AFRCWHEAT and SOILN calculated a lower NB which resulted in a much and slightly higher NUE, respectively. This may be because the available amount of nitrogen was underestimated. In the water-limited situation NB was reduced because drying of the top soil reduced the availability of soil and fertilizer nitrogen.

The time course of TB and green leaf area index (LAI) as observed in the irrigated Brimstone experiment during the growing season 1985/86 and as simulated with the different models is shown in Figure 5.7.1. TB was calibrated quite well in all models, but growth in the spring was strongly overestimated by SIRIUS and moderately overestimated by CERES. The time course of LAI was calibrated quite well in AFRCWHEAT and SOILN, was strongly overestimated by SIRIUS and strongly underestimated by NWHEAT and CERES. Dry matter production did not change much for LAI values varying between 4 and 8 and, hence, these differences in LAI had little effect on the prediction of TB.

The time course of ET and NB as observed in the irrigated Brimstone experiment during the growing season 1985/86 and as simulated with the different models is shown in Figure 5.7.2. ET was simulated quite accurately by all models. SIRIUS set the date of maturity and thus the end of transpiration too early, and AFRCWHEAT

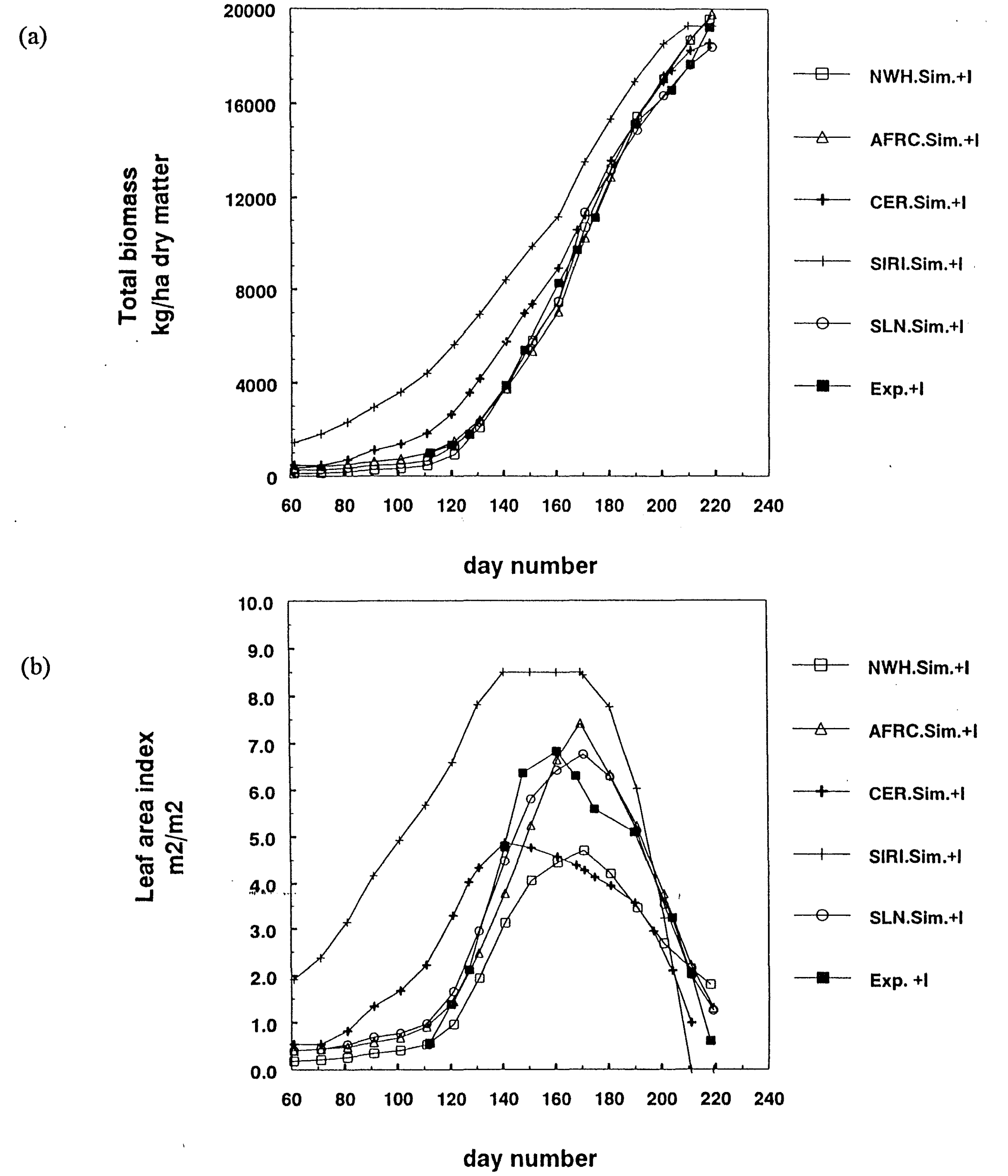


Figure 5.7.1 Time course of (a) total above-ground biomass and (b) green leaf area of winter wheat as observed in the Brimstone field trials (IACR-Rothamsted Experimental station, UK) for the treatment with irrigation (+I) and with a large fertilizer N application in growing season 1985/86 and as simulated with the NWHEAT (NWH.), AFRCWHEAT 3S (AFRC.), CERES-Wheat (CER.), SIRIUS (SIRI.) and SOILN-Wheat (SLN.) models for potential production.

slightly underestimated water losses by ET. Relatively poor calibration of LAI against the field trials for most models did not influence the successful calibration of ET. The time course of NB was simulated well by AFRCWHEAT, NWHEAT and SOILN. The AFRCWHEAT run, and the SOILN run to a lesser extent, showed a reduction of NB which was too strong at the end of the growing season. This was caused by either an underestimation of the total available amount of soil nitrogen or a decrease too early in the nitrogen uptake process. The overestimation of TB and leaf growth in spring by CERES resulted in nitrogen being taken up too rapidly in

(a)

(b)

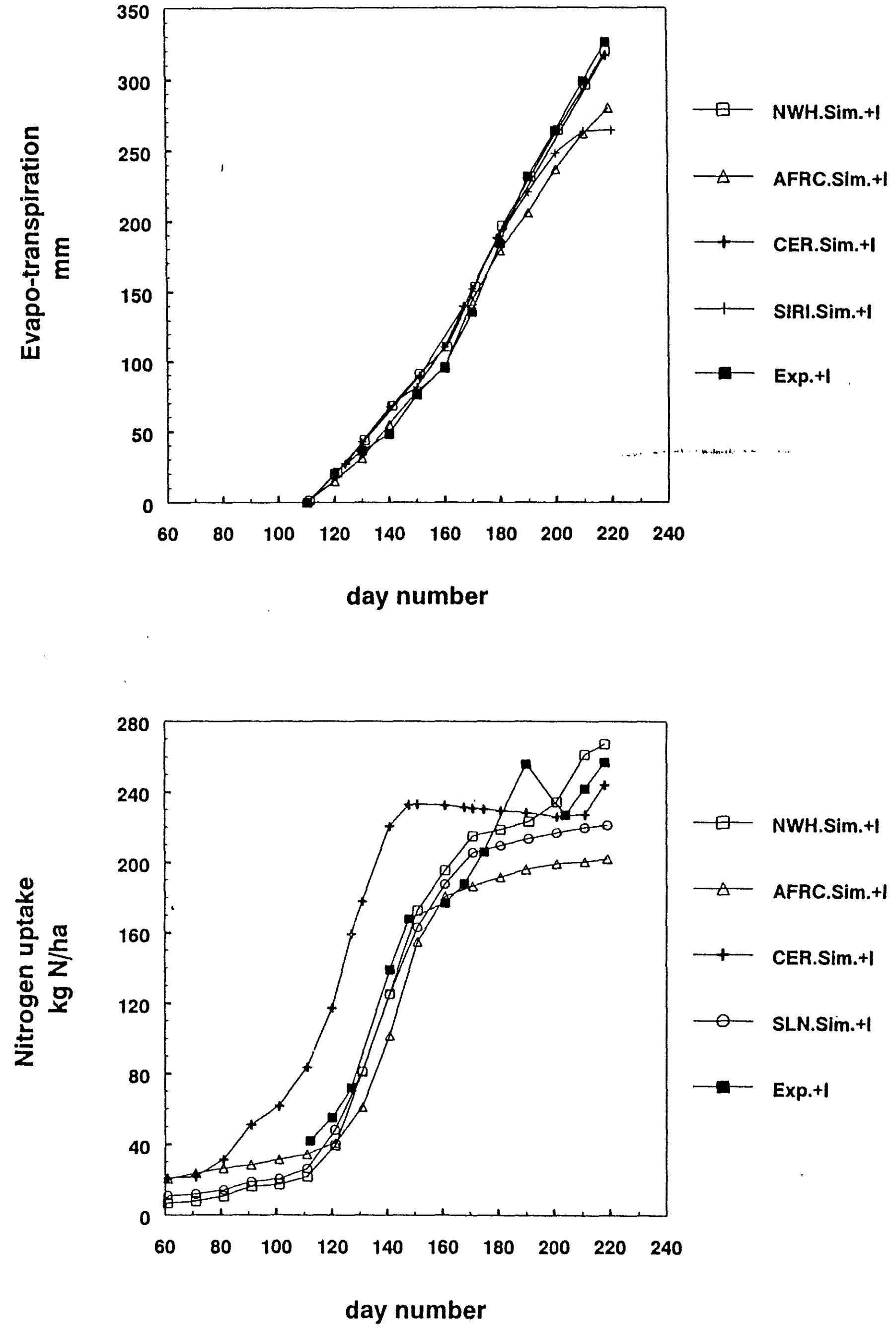


Figure 5.7.2 Time course of (a) evapotranspiration and (b) nitrogen uptake by winter wheat as observed in the Brimstone field trials (IACR-Rothamsted Experimental station, UK) for the treatment with irrigation (+I) and with a large fertilizer N application in growing season 1985/86 and as simulated with the NWHEAT (NWH.), AFRCWHEAT 3S (AFRC.), CERES-Wheat (CER.), SIRIUS (SIRI.) and SOILN-Wheat (SLN.) models for potential production.

spring, but NB at maturity corresponded well to the observed value.

Validation

Results from the Stackyard experiments during the growing season 1984/1985 were used to validate the different models (Table 5.7.2). The simulated and observed dates of anthesis (DA) corresponded reasonably well. The dates of maturity (DM) calculated by CERES and SIRIUS were reasonably close to the observed date, but those calculated with AFRCWHEAT and NWHEAT were approximately a week late. There are two explanations for this difference. First, both AFRCWHEAT and NWHEAT use a rather high base temperature for calculating the rate of post-anthesis phenological development which makes the length of the grain-filling period rather sensitive to changes in temperature. Second, nitrogen limitation in the field trial may have reduced the duration of grain-filling. SOILN needed a second calibration of phenological development or otherwise the modelled date of maturity would have been one month earlier than the observed date. The observed value for LAM was slightly lower than that in 1985/86. AFRCWHEAT, SOILN and SIRIUS calculated about the same value for LAM as in 1985/86 and NWHEAT and CERES a higher value. This resulted in slightly too low values for LAM in the CERES and NWHEAT runs, and slightly, moderately and much too high values in the SOILN, AFRCWHEAT, and SIRIUS runs, respectively.

Simulated TB and GR were high compared to those in the field trial, except those modelled with SOILN (Table 5.7.2). HI was too low in the SIRIUS run and too high in the NWHEAT run, this high value being mainly the result of a very long period of grain filling. In the water-limited situation, observed and simulated TB corresponded quite well, except for the SIRIUS run, and the CERES run to a lesser extent, in which the available amount of soil water was

Table 5.7.2 Plant characteristics as observed in the Stackyard wheat trials (fully irrigated (+I) or with rainshelter from 17 April (-I)) in 1984/85 at the IACR-Rothamsted Experimental station and as simulated by the different models.

	DE	DA	DM	GR	TB	HI	ET[1]	WUE[1]	RI	RUE	LAM	NB	NUE[2]
Observed +I	-	170	218	8.28	17.66	0.47	268[3]	5.54[3]	-	-	6.23	203	87.0
AFRCWHEAT +I	290	164	224	10.70	21.99	0.49	290	6.87	814	2.70	7.68	204	107.8
CERES Wheat +I	288	166	217	10.12	20.22	0.50	291	5.58	-	-	5.44	269	75.1
NWHEAT +I	290	169	225	11.84	22.33	0.53	309	6.73	849	2.63	5.70	296	75.5
SIRIUS +I	290	175	220	9.05	21.05	0.43	260	5.88	-	2.2	8.50	-	-
SOILN +I[4]	289	-	221	8.35	18.81	0.44	-	-	850	2.21	6.85	222	84.7
Observed -I		166	208	6.73	15.44	0.44	200[3]	6.67[3]	-	-	5.72	161	95.9
AFRCWHEAT -I	290	164	224	7.31	15.31	0.48	171	7.75	622	2.46	6.33	139	110.1
CERES Wheat -I	288	166	217	7.80	17.68	0.44	227	6.04	-	-	5.44	255	69.3
NWHEAT -I	290	169	225	5.65	15.82	0.36	197	7.24	798	1.98	5.58	188	84.2
SIRIUS -I	290	175	220	7.78	20.35	0.38	236	6.18	-	2.2	8.50	-	-

1 Evapotranspiration and water use efficiency from day 110 to maturity.
2 For the meaning of the abbreviations see Section 5.7.2.
3 Observed evapotranspiration and water use efficiency from day 110 to day 210.
4 This model needed a new calibration of the rate of phenological development against Stackyard data as otherwise the date of maturity would be one month too early.

overestimated. In the experiment water shortage resulted in a slightly lower HI. According to the simulation with AFRCWHEAT, water shortage did not affect HI, and according to those with CERES, SIRIUS and NWHEAT, water shortage reduced HI moderately, moderately and strongly, respectively.

Observed values for ET covered the period from day 110 to day 210, whilst simulated values covered a period which was 7 to 15 days longer (Table 5.7.2). Taking this difference into account, the simulated ET values in the irrigated situation corresponded well to observed values. In the water-limited situation, ET was determined by the soil water supply which was underestimated in the AFRCWHEAT run and overestimated in the CERES and SIRIUS runs. WUE was higher in the water-limited situation than in the irrigated situation because water losses by soil evaporation have been reduced.

In the irrigated trial RUE calculated with AFRCWHEAT and NWHEAT was higher than the RUE calculated with SIRIUS and SOILN. In the AFRCWHEAT run water shortage reduced LAI, and thus RI, more strongly than in the NWHEAT run. This resulted in a smaller decrease in RUE by water shortage in the AFRCWHEAT run.

The observed value for NB in the irrigated trial was simulated well by AFRCWHEAT (Table 5.7.2). SOILN, CERES and NWHEAT calculated slightly, much and much too high values for NB, respectively. It is probable that the nitrogen supply in the field trial was not sufficient to attain the potential yield level. This resulted in reduced TB and a relatively high NUE. In the water-limited field trial the nitrogen supply was reduced by drying of the top soil, which resulted in a lower value for observed NB and an even higher NUE. AFRCWHEAT and NWHEAT also simulated a reduced NB for the water-limited situation.

The time course of TB and LAI as observed in the irrigated Stackyard experiment during the growing season 1984/85 and as simulated with the different models is shown in Figure 5.7.3. TB was simulated reasonably well by AFRCWHEAT, NWHEAT and SOILN up to day 180 when the observed growth curve started to flatten off. This part of the curve was only simulated well by SOILN. Growth in spring was strongly overestimated by SIRIUS and moderately overestimated by CERES. The time course of LAI was simulated well only by SOILN. This was partly caused by the difference between the observed and simulated date of maturity for AFRCWHEAT and NWHEAT (Table 5.7.2). LAI was slightly and strongly overestimated by AFRCWHEAT and SIRIUS respectively and slightly underestimated by both NWHEAT and CERES.

The time course of ET and NB as observed in the irrigated Stackyard experiment during the growing season 1984/85 and as simulated with the different models is shown in Figure 5.7.4. ET was simulated quite accurately by all models. In the field trial, however, crop growth and transpiration stopped at an earlier date. Differences in LAI between simulations and experimental data do not appear to influence these results. The time course of NB was simulated reasonably well by AFRCWHEAT, NWHEAT and SOILN up to day 150. From that date the rate of nitrogen uptake in the field trial became very small because of depletion of the soil supply. This was only simulated well by AFRCWHEAT and SOILN. The overestimation of TB and leaf growth in spring by CERES resulted in nitrogen being taken up too rapidly during this period, but NB at maturity corresponded to values calculated with the NWHEAT model.

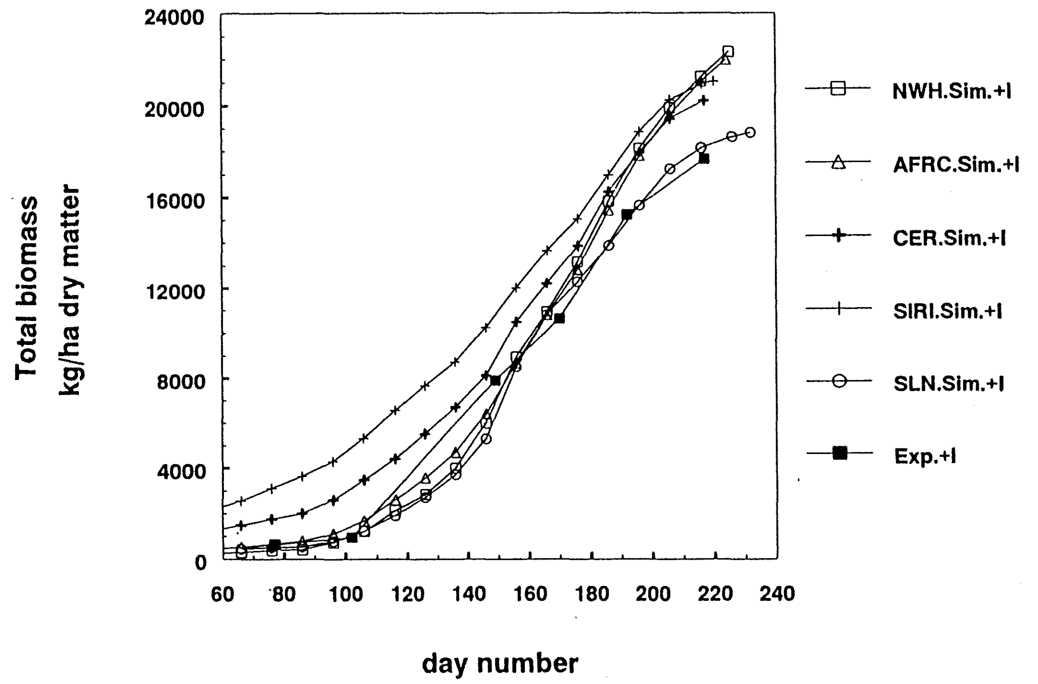
5.7.4.2 *Sevilla*

Wheat variety trials were carried out at Tomejil in the neighbourhood of Sevilla. The varieties were grown on a heavy clay (vertisol). Large amounts of fertilizer were applied, but no irrigation water. In the trial carried out during the growing season 1988/89 (RAEA, 1989), and used for calibration, the crop was sown on 7 December 1988. In the trial carried out in 1990/91 (RAEA, 1991), and used for validation, the crop was sown on 29 November 1990. Dates of emergence, anthesis and harvest were recorded in all trials. Grain yields were also available for each variety and the average of the three highest yields was used for comparison against simulated yields.

Other information on the time course of biomass, water use, nitrogen use and leaf area during the growth period was not available. Therefore, such results from the model runs were compared between models, but not against observed data.

The initial and maximum amounts of available water assumed in all model runs were based on data from A. Iglesias (pers. comm., 1995). Historical sets of weather data were used. The initial amounts of available water in the CERES

(a)



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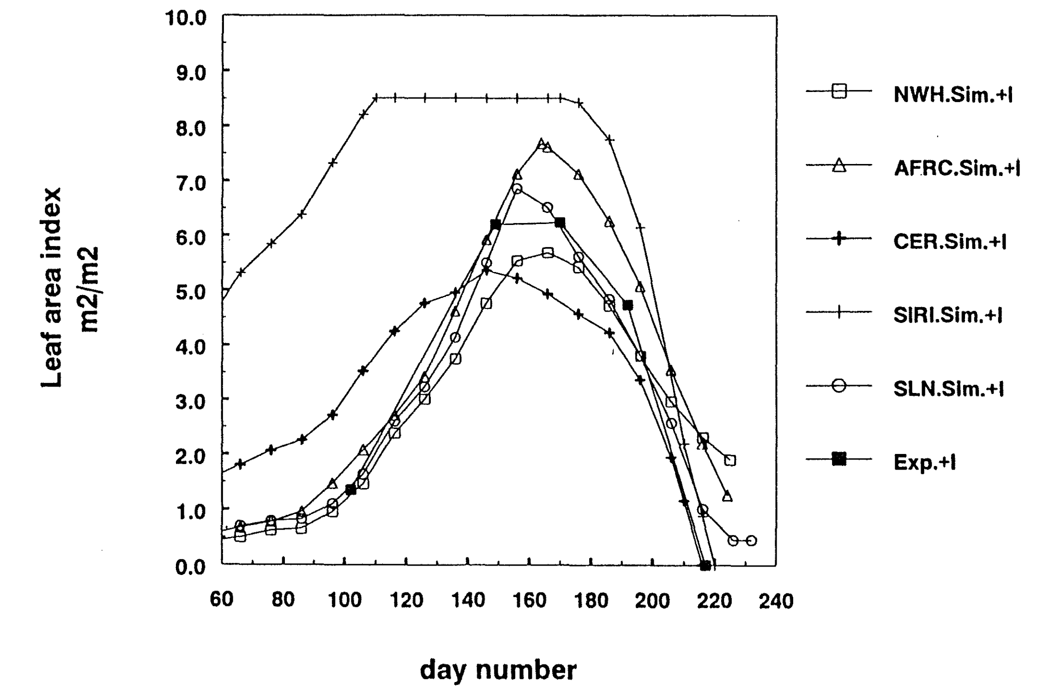


Figure 5.7.3 Time course of (a) total above-ground biomass and (b) green leaf area of winter wheat as observed in the Stackyard field trials (IACR-Rothamsted Experimental station, UK) for the treatment with irrigation (+I) and with a large fertilizer N application in growing season 1984/85 and as simulated with the NWHEAT (NWH.), AFRCWHEAT 3S (AFRC.), CERES-Wheat (CER.), SIRIUS (SIRI.) and SOILN-Wheat (SLN.) models for potential production.

and NWHEAT runs may have been estimated too high as they were set to field capacity at sowing. As large amounts of fertilizer N were applied in the variety trials, it was assumed that in the simulations N supply was not limiting for crop growth and N uptake.

Calibration

An overview of model results and the observed data for the calibration year (1988/89) is given in Table 5.7.3. All results except DE, DA and LAM are given for the date of maturity. The simulated

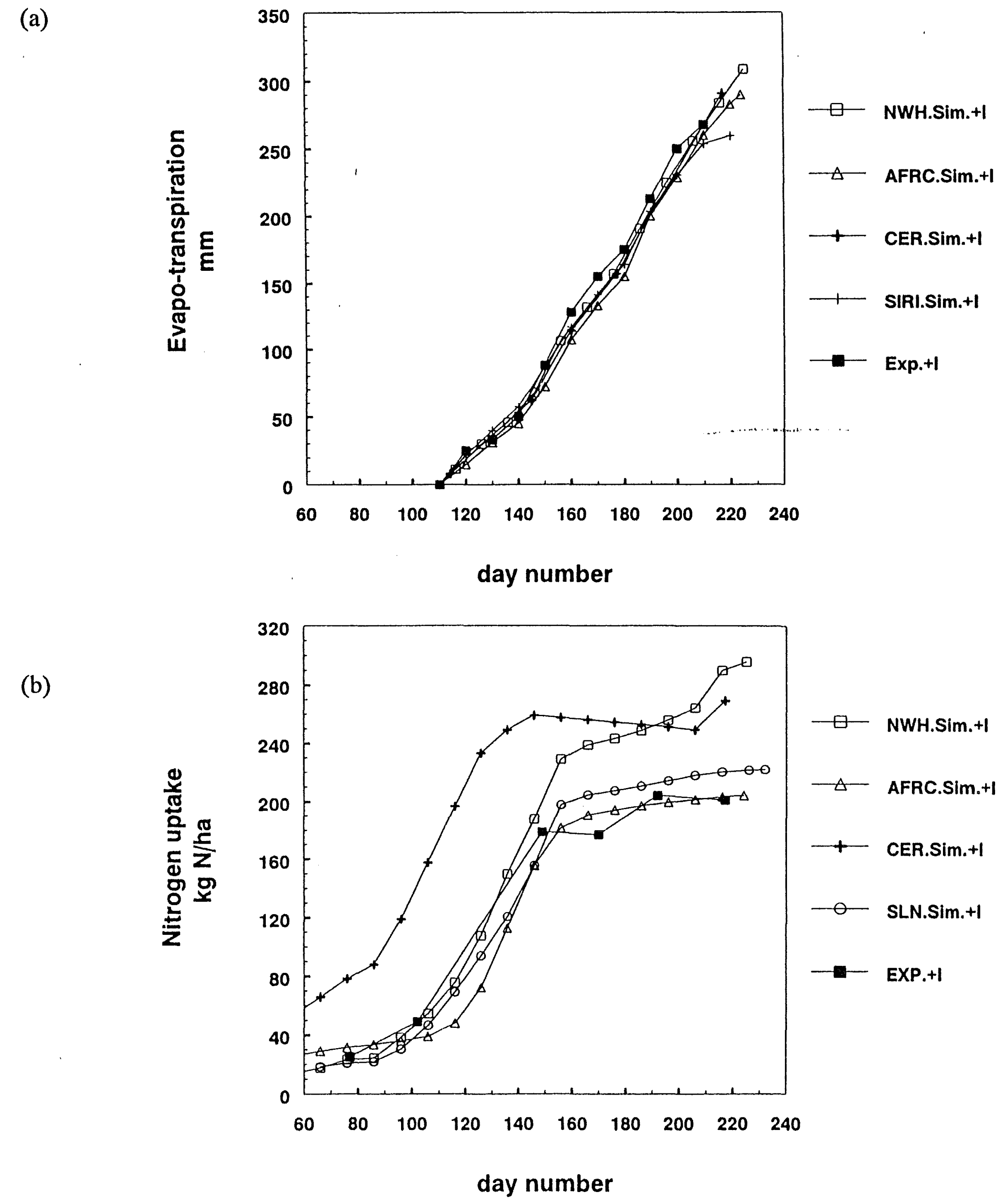


Figure 5.7.4 Time course of (a) evapotranspiration and (b) nitrogen uptake by winter wheat as observed in the Stackyard field trials (IACR-Rothamsted Experimental station, UK) for the treatment with irrigation (+I) and with a large fertilizer N application in growing season 1984/85 and as simulated with the NWHEAT (NWH.), AFRCWHEAT 3S (AFRC.), CERES-Wheat (CER.), SIRIUS (SIRI.) and SOILN-Wheat (SLN.) models for potential production.

dates of emergence (DE) and anthesis (DA) were calibrated well in all models (Table 5.7.3). The date of maturity was not available from the variety trials. A slightly later date of maturity was calculated by AFRCWHEAT and SIRIUS than CERES and NWHEAT. The highest values for LAM were calculated with AFRCWHEAT and SIRIUS and the lowest with CERES and NWHEAT. These differences were also found at Rothamsted. An observed value for LAM was not available.

In the water-limited situation the highest value for TB was calculated with NWHEAT and the lowest value with AFRCWHEAT (Table 5.7.3). HI was higher for the irrigated situation than for the water-limited situation. In water-limited conditions, AFRCWHEAT calculated the highest value for HI and CERES and SIRIUS the lowest values. The calibration of GR was not as accurate as phenology. The CERES model corresponded best, the AFRCWHEAT and SIRIUS results were slightly too low and the NWHEAT result was too high. These differences might be explained by, firstly, the amount of initial soil water at sowing might be overestimated in the simulations (at least for CERES and NWHEAT) and, secondly, in variety trials yield losses often occur due to ripening diseases and sub-optimum crop management.

Observed values for water losses by ET were not available. Simulated ET in the CERES and SIRIUS runs were relatively high whilst ET from AFRCWHEAT was very low, probably because this model used a much lower estimate for the soil water supply than the other models (Table 5.7.3). This resulted in WUE values that varied from a relatively high value in the AFRCWHEAT run to low values in the CERES and SIRIUS runs.

RI in the AFRCWHEAT run was much lower than in the NWHEAT run. This might explain the low values for TB and ET calculated with AFRCWHEAT. RUE, however, was almost identical in both model runs and in the SIRIUS run.

Calculated values for NB differed mainly because of differences in TB (Table 5.7.3). CERES and NWHEAT calculated identical NUE, with a slightly higher value in the case where soil water supply was non-limiting.

Table 5.7.3 Plant characteristics as simulated by the different models for potential (+I) and water-limited production (-I) for winter wheat growing in 1988/89 at Tomejil near Sevilla and as observed in the wheat variety trials at Tomejil.

	DE	DA	DM	GR	TB	HI	ET[1]	WUE[1]	RI	RUE	LAM	NB	NUE[2]
CERES Wheat +I	358	107	145	7.18	17.45	0.41	425	4.11	-	-	5.59	241.7	72.2
NWHEAT +I	358	105	145	9.47	20.10	0.47	354	5.68	753	2.67	5.30	281.7	71.3
Observed -I	359	105	-	6.27[3]	-	-	-	-	-	-	-	-	-
AFRCWHEAT -I	358	107	151	5.49	12.16	0.45	181	6.72	527	2.31	7.52	221.0	55.0
CERES Wheat -I	358	107	145	5.99	16.09	0.37	355	4.53	-	-	5.59	241.7	66.6
NWHEAT -I	358	105	145	7.57	18.15	0.42	304	5.98	745	2.44	5.26	276.9	65.6
SIRIUS -I	358	106	149	5.60	14.71	0.38	358	4.10	-	2.2	8.50	-	-

1 Evapotranspiration and water use efficiency from emergence to maturity.
2 For the meaning of the abbreviations see Section 5.7.2.
3 Average of three highest grain yields in variety trial.

In the AFRCWHEAT run the water supply was strongly limiting which resulted in the lowest value for NUE.

The time course of TB and LAI as simulated with the different models for water-limited production in the 1988/89 growing season is shown in Figure 5.7.5. The time course of TB was very similar for NWHEAT and CERES up to day number 120, after which the CERES curve flattens off at an earlier date than NWHEAT near maturity. SIRIUS calculated a smaller increase in TB during the main growth period than the other models. In the AFRCWHEAT run crop growth started at a later date, but from day 70 the rate of increase in TB was almost identical to those in the NWHEAT and CERES runs. However, growth stopped at an earlier date, probably because the soil water supply was more limited. The time courses of LAI as calculated with the different models were similar to those simulated for the field trials in Rothamsted (Figures 5.7.1

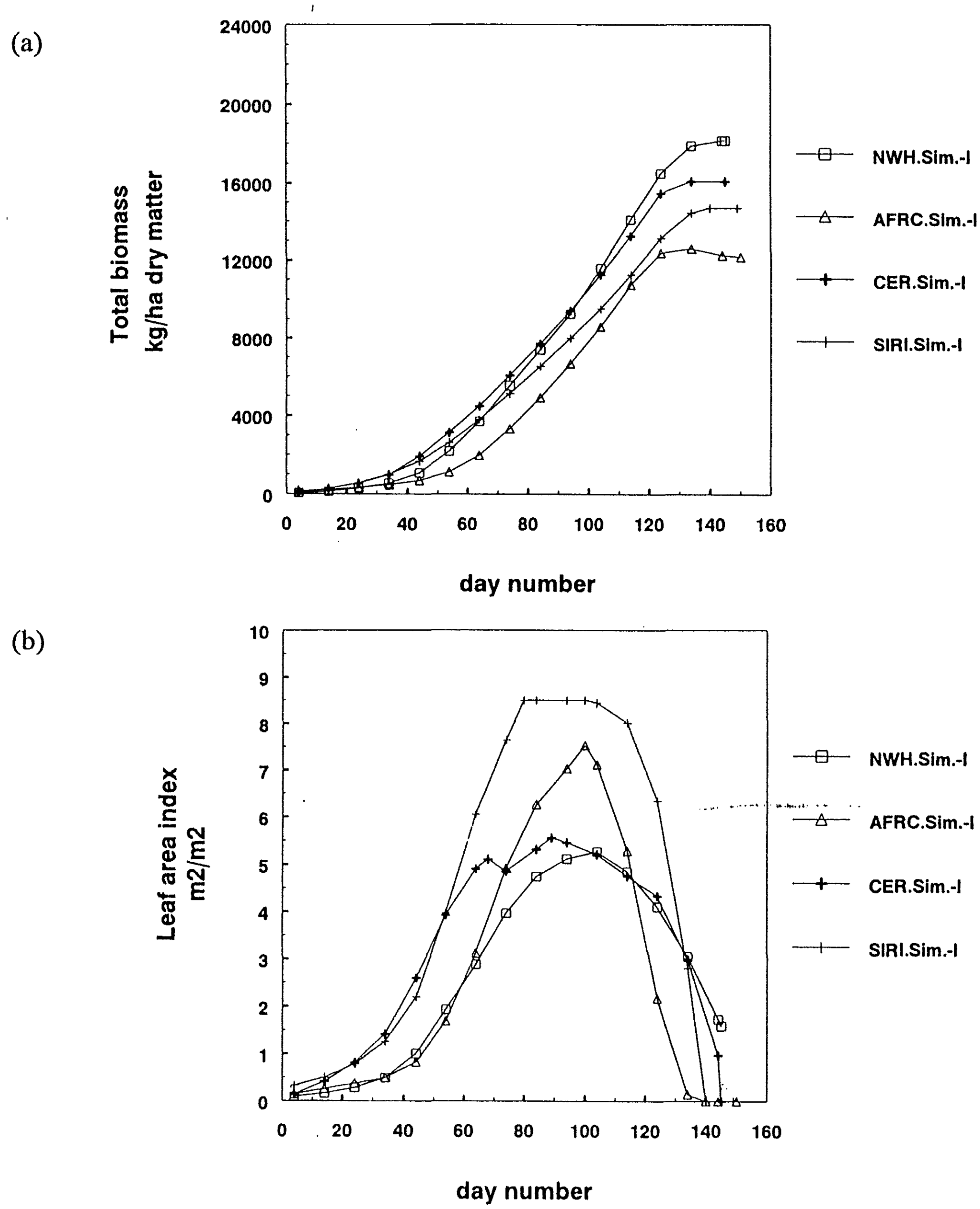
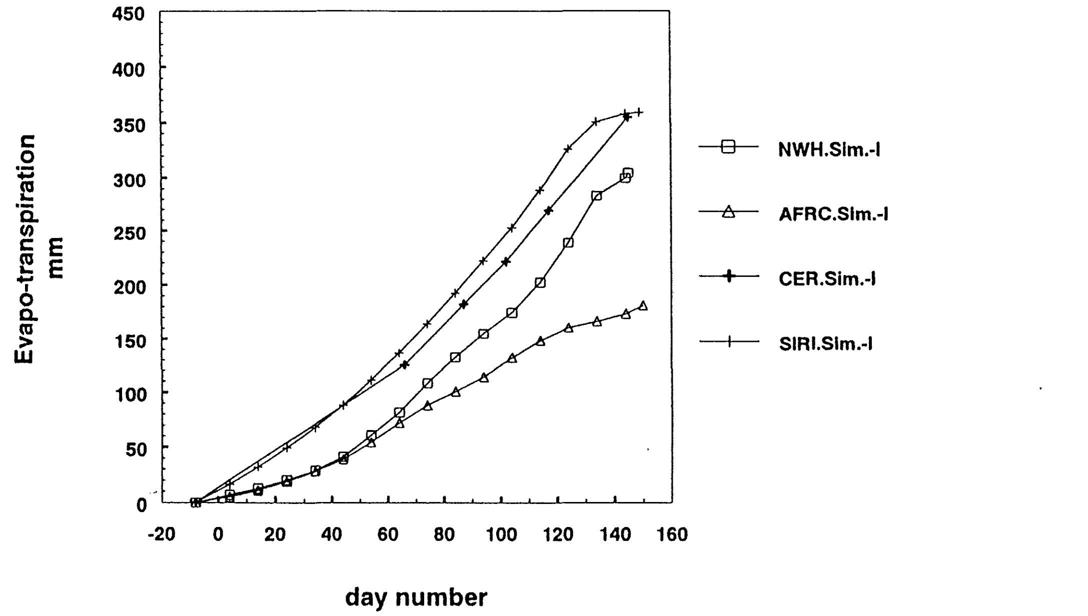


Figure 5.7.5 Time course of (a) total above-ground biomass and (b) green leaf area of winter wheat as simulated with the NWHEAT (NWH.), AFRCWHEAT 3S (AFRC.), CERES (CER.), and SIRIUS (SIRI.) models for water-limited production (-I) in growing season 1988/89 at Tomejil (near Sevilla), Spain.

and 5.7.3). CERES and NWHEAT gave relatively low values for LAI, with an earlier increase in the CERES run. AFRCWHEAT simulated a relatively late start of leaf area growth which resulted in a rather high maximum value, followed by a very early and drastic decrease in LAI, probably because of water shortage. SIRIUS simulated the highest values as LAI is fixed at 8.5 around the time of anthesis.

The time course of ET and NB as simulated with the different models for water-limited production in the 1988/89 growing season is shown in Figure 5.7.6. ET during the initial part of the growing season was relatively high in the SIRIUS and CERES runs, which is explained by the high values for LAI. During the rest of the growing season all models calculated the same rate of ET except for AFRCWHEAT, probably because its

(a)



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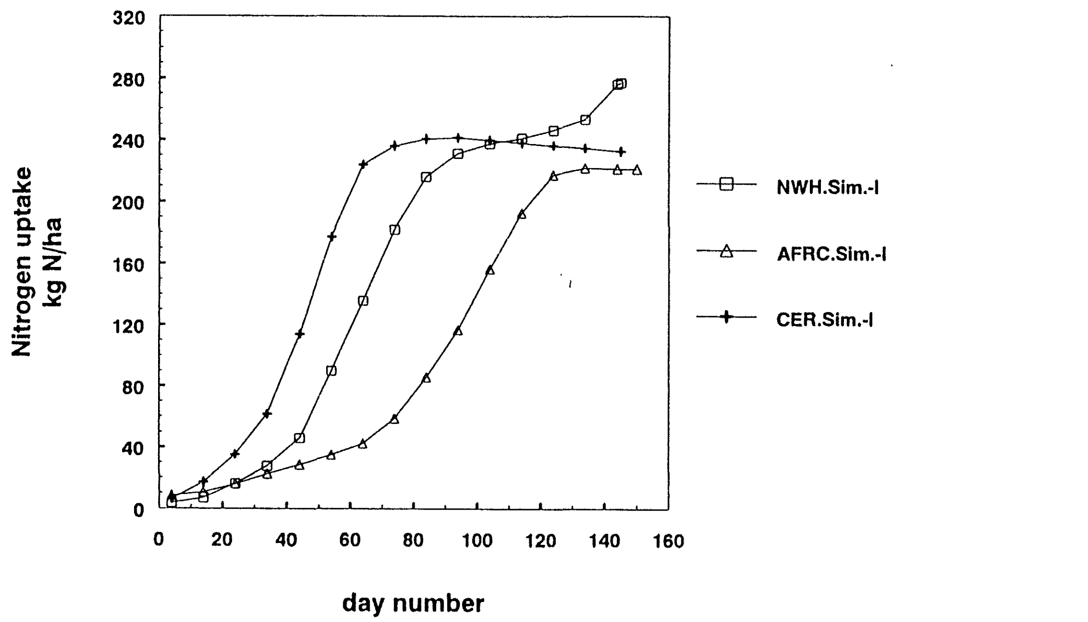


Figure 5.7.6 Time course of (a) evapotranspiration and (b) nitrogen uptake by winter wheat as simulated with the NWHEAT (NWH.), AFRCWHEAT 3S (AFRC.), CERES (CER.), and SIRIUS (SIRI.) models for water-limited production (-I) in growing season 1988/89 at Tomejil (near Sevilla), Spain.

soil water supply was more limiting. The initial rate of increase in NB was greatest in the CERES run, which was partly caused by the early start of crop growth (Figure 5.7.5) and was partly due to model characteristics (Figures 5.7.2 and 5.7.4). NB was lowest in the AFRCWHEAT run because of the late start of crop growth (Figure 5.7.5) and perhaps due to reduced nitrogen availability in the dry soil.

Validation

Results from the wheat variety trials in 1990/91 were too limited for a thorough validation of all crop parameters. For those parameters for which observations were not available, model results were compared between models (Table 5.7.4). All models calculated dates of emergence (DE) that corresponded well to the observed date. The modelled dates of anthesis (DA) were almost identical between models, but were later than the observed date. The date of maturity (DM) was not observed in the variety trials. SIRIUS and AFRCWHEAT calculated slightly later dates of maturity than the CERES and NWHEAT models. The highest value for LAM were again calculated in the SIRIUS and AFRCWHEAT runs and the lowest in the CERES and NWHEAT runs.

NWHEAT calculated the highest value for TB and AFRCWHEAT the lowest value (Table 5.7.4). Highest HI and GR was calculated by NWHEAT. The other models calculated a lower HI and a much lower GR which corresponded well with the best GR in the variety trials. These observed GR may not be completely comparable to the simulated GR if in the trials GR losses due to ripening diseases and sub-optimum crop management were not negligible.

ET was highest in the CERES and SIRIUS runs and lowest in the AFRCWHEAT run (Table 5.7.4). This resulted in the highest WUE for the AFRCWHEAT run and the lowest for CERES and SIRIUS runs. In irrigated conditions WUE was lower because of increased water losses by soil evaporation. NWHEAT calculated the highest NB because of the high TB (Table 5.7.4). This resulted in a NUE that was slightly lower than that calculated by CERES. In the AFRCWHEAT run water supply was strongly limiting which resulted in the lowest NUE.

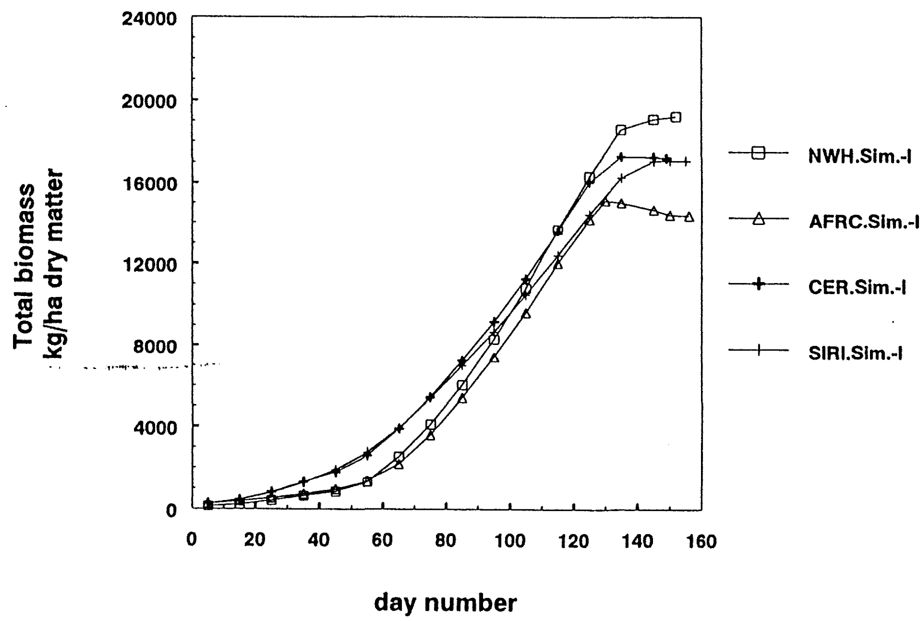
Table 5.7.4 Plant characteristics as simulated by the different models for potential (+I) and water-limited production (-I) for winter wheat growing in 1990/91 at Tomejil near Sevilla and as observed in the wheat variety trials at Tomejil.

	DE	DA	DM	GR	TB	HI	ET	WUE[1]	RI	RUE	LAM	NB	NUE[2]
CERES Wheat +I	347	110	150	8.26	18.88	0.44	463	4.08	-	-	5.57	233.8	80.8
NWHEAT +I	349	109	152	10.16	20.87	0.49	351	5.95	824	2.53	5.03	285.9	73.0
Observed -I	348	104	-	6.06[3]	-	-	-	-	-	-	-	-	-
AFRCWHEAT -I	347	108	156	5.49	14.36	0.38	195	7.38	644	2.23	7.86	255.0	56.3
CERES Wheat -I	347	110	150	6.77	17.18	0.39	382	4.50	-	-	5.57	233.8	73.5
NWHEAT -I	349	109	152	8.52	19.21	0.44	296	6.50	818	2.35	5.03	282.5	68.0
SIRIUS -I	349	111	155	6.18	17.06	0.36	394	4.33	-	2.2	8.50	-	-

1 Evapotranspiration and water use efficiency from emergence to maturity.
2 For the meaning of the abbreviations see Section 5.7.2.
3 Average of three highest grain yields in variety trial.

The time course of TB and LAI as simulated with the different models for water-limited production in the 1990/91 growing season is shown in Figure 5.7.7. The time course of TB in the different model runs were similar, except that in the CERES and SIRIUS runs growth started earlier than in the other two model runs. Near maturity growth stopped at a relatively early date in the AFRCWHEAT run, probably because of water shortage, and at a relatively late date in the NWHEAT run. SIRIUS calculated a smaller increase in TB during the main growth period than the other models. The time courses of LAI were similar to those simulated for the other site and/or year.

(a)



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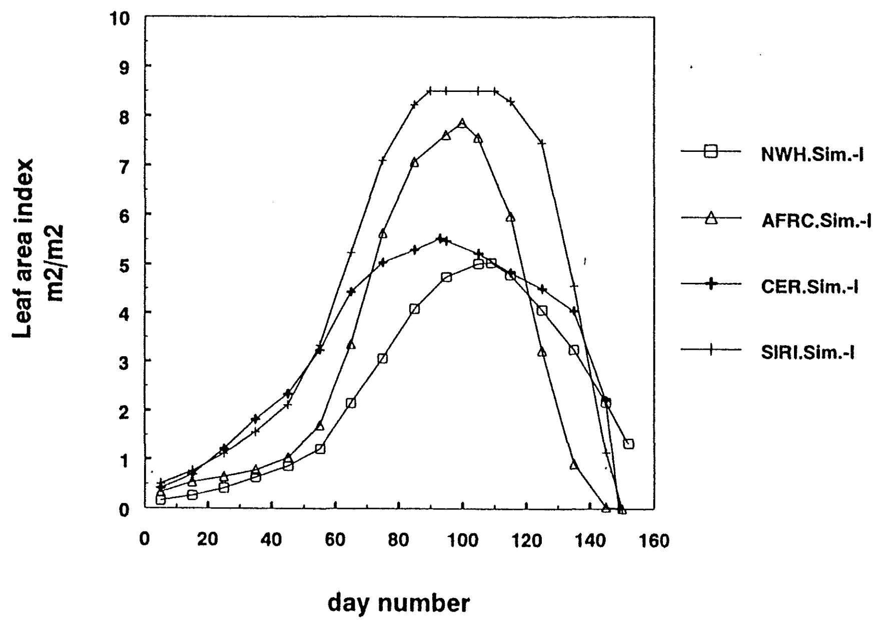
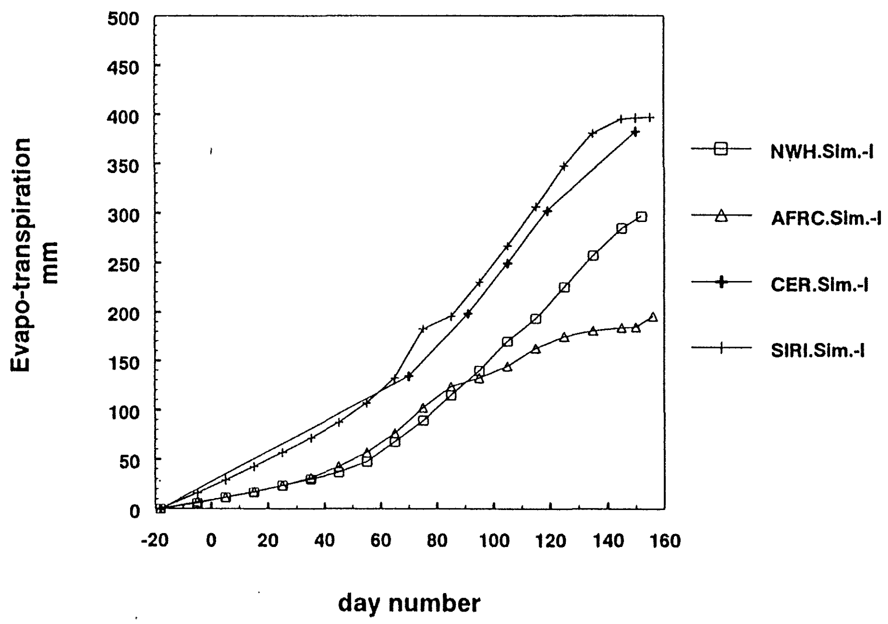


Figure 5.7.7 Time course of (a) total above-ground biomass and (b) green leaf area of winter wheat as simulated with the NWHEAT (NWH.), AFRCWHEAT 3S (AFRC.), CERES (CER.), and SIRIUS (SIRI.) models for water-limited production (-l) in growing season 1990/91 at Tomejil (near Sevilla), Spain.

The time course of ET and NB as simulated with the different models for water-limited production in the 1990/91 growing season is shown in Figure 5.7.8. ET during the initial part of the growing season was relatively high in the SIRIUS and CERES runs, which was caused by the high values for LAI. During the rest of the growing season all models calculated approximately the same rate of ET. In the AFRCWHEAT run ET was reduced strongly from day 100, probably because of limiting soil water supply. The time courses of NB were similar to those simulated for the calibration year.

(a)



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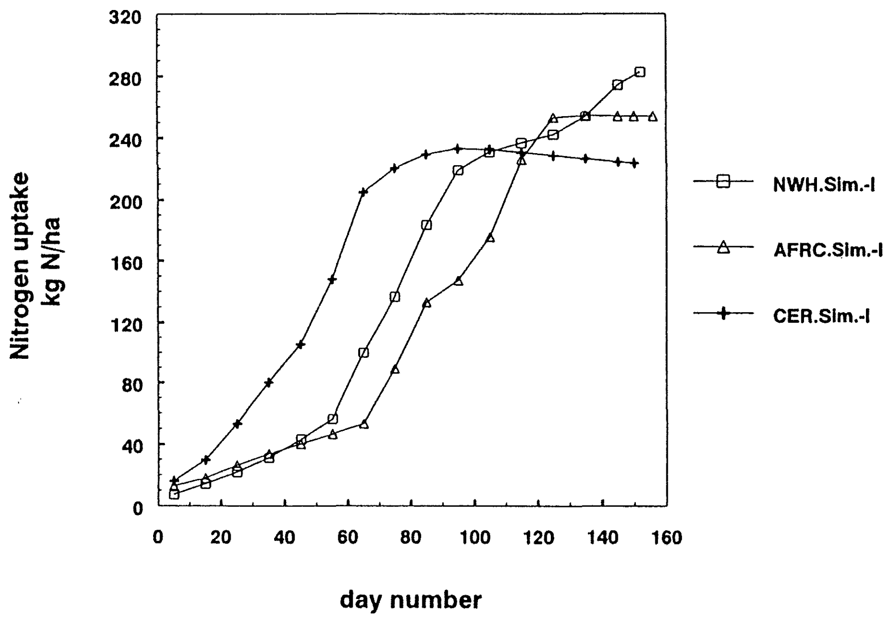


Figure 5.7.8 Time course of (a) evapotranspiration and (b) nitrogen uptake by winter wheat as simulated with the NWHEAT (NWH.), AFRCWHEAT 3S (AFRC.), CERES (CER.), and SIRIUS (SIRI.) models for water-limited production (-I) in growing season 1990/91 at Tomejil (near Sevilla), Spain.

5.7.5 Model sensitivity to systematic changes in climate

A baseline climate data set for a time period of 30 years has been generated on the basis of an historical weather data set using the LARS-WG stochastic weather generator (Racsko *et al.*, 1991; Barrow and Semenov, 1995). Weather variables in the baseline data set were adjusted independently, in a stepwise manner, in order to gauge the sensitivity of model results to changing values of each variable. The following output variables from crop growth simulations were compared: total biomass yield, grain yield, cumulative evapotranspiration (from sowing to maturity) and CV of grain yield. For each output variable, reported values are the mean result of 30 years of crop growth simulations. Five models have been used, of which CERES and NWHEAT calculated results for both potential and water-limited production, whilst SOILN calculated results for only potential production and AFRCWHEAT and SIRIUS calculated results for only water-limited production.

Three climatic variables were systematically adjusted. Firstly, the amount of precipitation was varied which affected the duration and degree of water shortage and, thus, crop growth and transpiration. Secondly, the atmospheric CO_2 concentration was varied which affected both the CO_2 assimilation rate and crop transpiration rate and, hence, crop growth. Finally, temperature was varied which mainly resulted in changes in the rate of phenological development and, thus, in the length of the vegetative and grain-filling periods. These analyses were carried out for the two sites, Rothamsted and Sevilla, and for both mean changes in climatic variables and for changes in climatic variability.

5.7.5.1 *Rothamsted: mean changes in climate*

For winter wheat in Rothamsted, increasing rainfall resulted in an increase in TB and GR in the absence of irrigation (Figure 5.7.9a, b). These increases in TB and GR appeared to be much larger in the NWHEAT run than in the other model runs. This was because the soil water storage assumed in the NWHEAT simulation was much smaller than in the other models. This also explains why ET increased more strongly with the amount of precipitation in the NWHEAT run than in the other model runs (Figure 5.7.9c). AFRCWHEAT calculated a relatively low value for ET. CV of grain yield almost did not change with the amount of precipitation in the AFRCWHEAT, CERES and SIRIUS runs, probably because of the limited degree of water shortage, but decreased strongly in the NWHEAT run with its much smaller soil water supply.

Increasing concentrations of atmospheric CO_2 resulted in about the same increases in TB and GR in all model runs (Figure 5.7.10a, b). The CO_2 effect on yield was linear in the AFRCWHEAT, CERES and SIRIUS runs but curved according to NWHEAT. The NWHEAT model includes interactions between CO_2 and temperature. At low temperatures the CO_2 effect becomes nil and this interaction limits the CO_2 effect to a greater degree at higher CO_2 concentrations. Secondly, increasing CO_2 changes the CO_2 assimilation - light response curve in a partly non-linear way. CERES showed no sensitivity to a decrease in CO_2 concentration below the present level. ET increased slightly with increasing atmospheric CO_2 in the AFRCWHEAT and SIRIUS runs and decreased slightly and considerably in the NWHEAT and CERES runs, respectively (Figure 5.7.10c). This decrease was caused by the decrease in stomatal conductance with increasing atmospheric CO_2. CV of grain yield did not change with increasing atmospheric CO_2, except in the NWHEAT water-limited run. In this run, water shortage reduced the yield to a large extent resulting in a high CV of grain yield for baseline conditions. Increases in atmospheric CO_2 caused a higher water use efficiency and a smaller yield reduction by water shortage resulting in a lower value for the CV (see Figure 5.7.10d).

Increases in temperature resulted in advancement of the date of maturity and a decrease in the duration of the grain-filling period. At the lowest temperature (-4°C) the date of anthesis was so late that only a short period was available for grain filling and, according to AFRCWHEAT, grains did not become mature in a number of

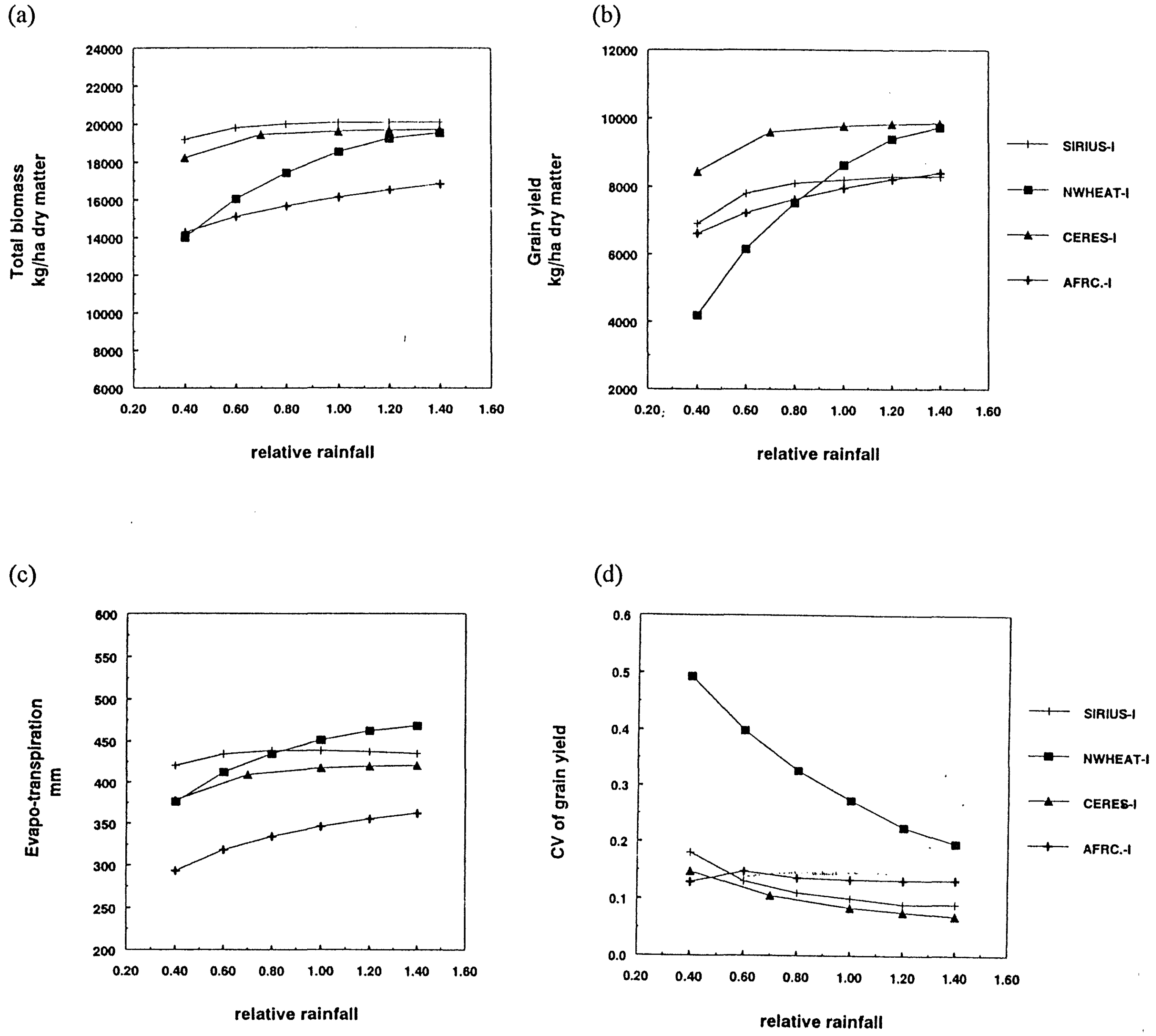


Figure 5.7.9 Sensitivity to precipitation of (a) total biomass (b) grain yield (c) cumulative evapotranspiration (from sowing to maturity) and (d) coefficient of variation (CV) of grain yield of winter wheat in Rothamsted, U.K. as simulated with the SIRIUS, NWHEAT, CERES and AFRCWHEAT 3S (AFRC.) models for water-limited (-l) production.

years. Furthermore, the CO_2 assimilation rate and, hence, the growth rate were reduced at low at low temperatures in some of the models (at least NWHEAT). Therefore, low values for GR and TB were simulated with large increases in temperature and in some models also with large decreases in temperature (Figure 5.7.11a, b: low yield in NWHEAT run and no yield in AFRCWHEAT run). The SIRIUS run showed a stronger decrease in TB with rising temperature than the other model runs. Yield sensitivity to temperature was similar for all models, both in the potential and the water-limited situation, but considerable differences in yield level occurred.

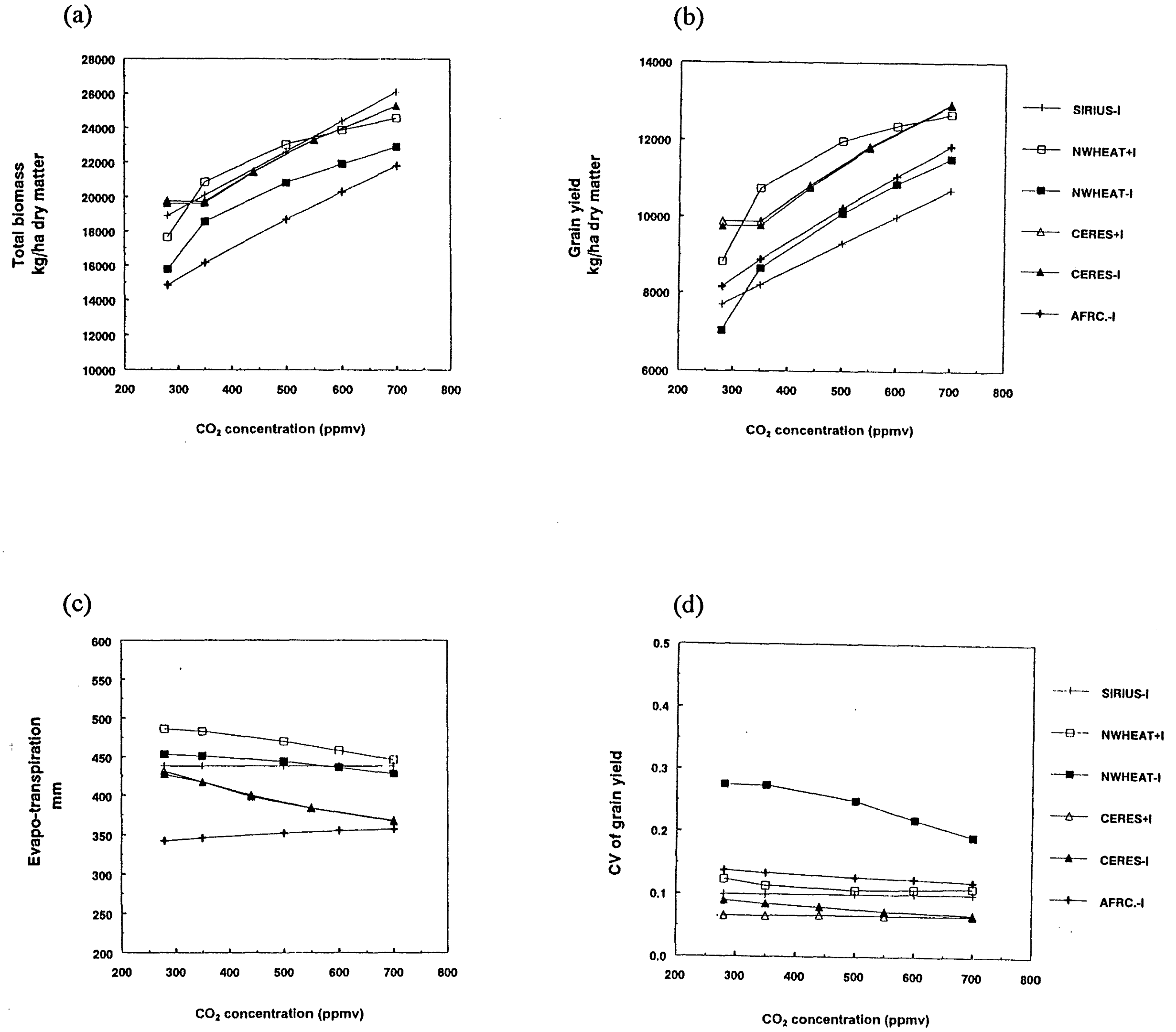


Figure 5.7.10 Sensitivity to atmospheric CO_2 concentration of (a) total biomass (b) grain yield (c) cumulative evapotranspiration (from sowing to maturity) and (d) coefficient of variation (CV) of grain yield of winter wheat in Rothamsted, U.K. as simulated with the SIRIUS, NWHEAT, CERES and AFRCWHEAT 3S (AFRC.) models for potential (+I) and water-limited (-I) production.

Water losses by ET decreased strongly and slightly with rising temperature in the CERES and NWHEAT runs respectively (Figure 5.7.11c), mainly because of advancement of the date of maturity. AFRCWHEAT calculated a relatively low ET that was unaffected by temperature change. SIRIUS calculated a large decrease in ET for decreases in temperature. The coefficient of variation (CV) of grain yield did not change with temperature change (Figure5.7.11d). Only with -4°C change, CV increased in the NWHEAT and SIRIUS runs and at +4°C and +6°C in the AFRCWHEAT run. NWHEAT calculated a higher CV for water-

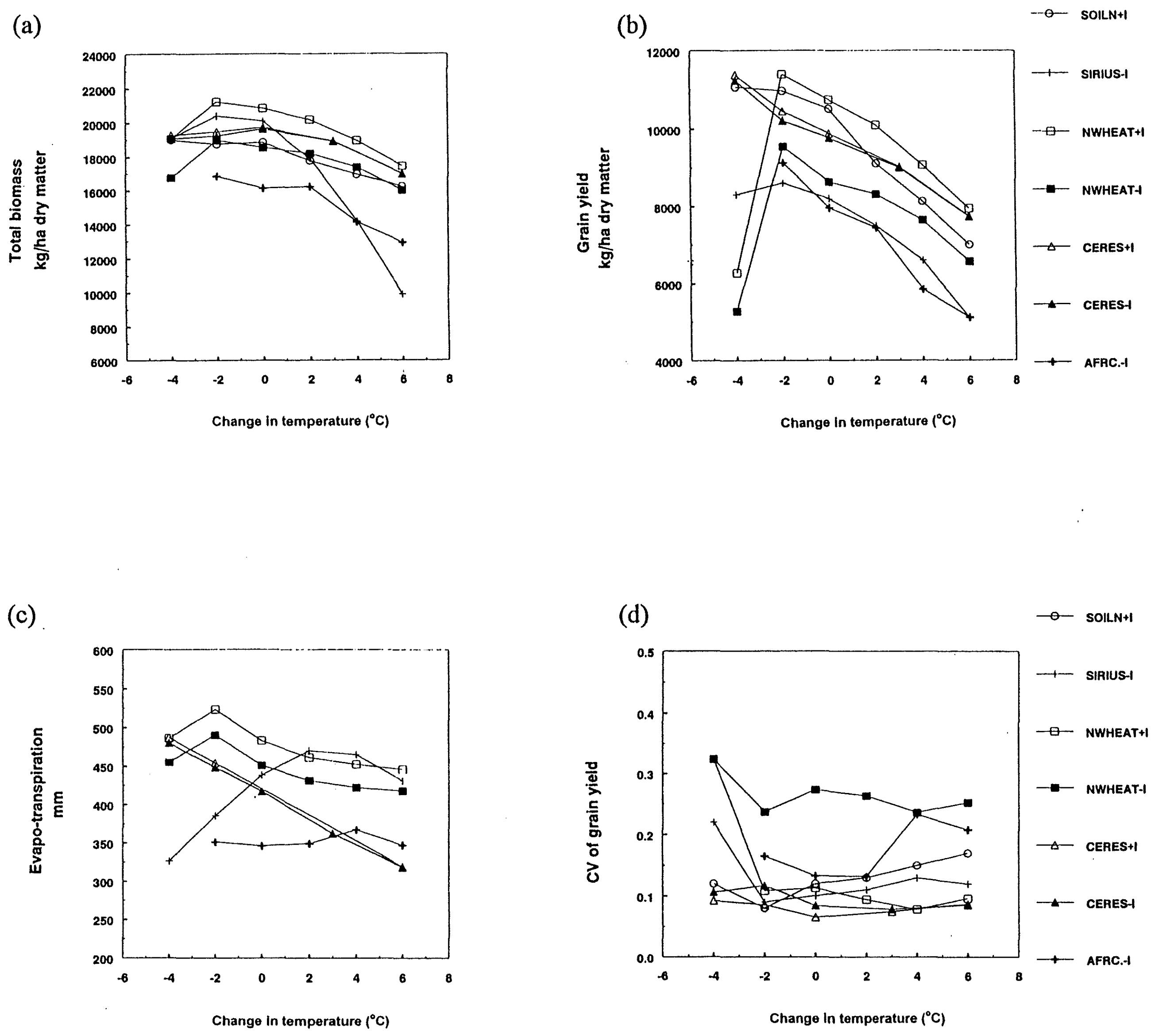


Figure 5.7.11 Sensitivity to temperature of (a) total biomass (b) grain yield (c) cumulative evapotranspiration (from sowing to maturity) and (d) coefficient of variation (CV) of grain yield of winter wheat in Rothamsted, U.K. as simulated with the SOILN, SIRIUS, NWHEAT, CERES and AFRCWHEAT 3S (AFRC.) models for potential (+I) and water-limited (-I) production.

limited production than for potential production, i.e. the increasing risk of water shortage increased the variation in yield.

5.7.5.2 *Rothamsted: changes in climatic variability*

Two changes in climatic variability have been analysed: a doubling of the daily variability of temperature and a doubling of the length of dry spells. The doubling in temperature variability was applied in conjunction with changes in mean temperature, comparable to those in Section 5.7.5.1. Higher temperatures gave a decrease in TB which was strongest in the SIRIUS run, and a decrease in GR that was about the same in all model runs (Figure 5.7.12 a, b). This decrease can be explained from the advanced date of maturity and the shorter period of grain filling at higher temperatures. Doubled temperature variability

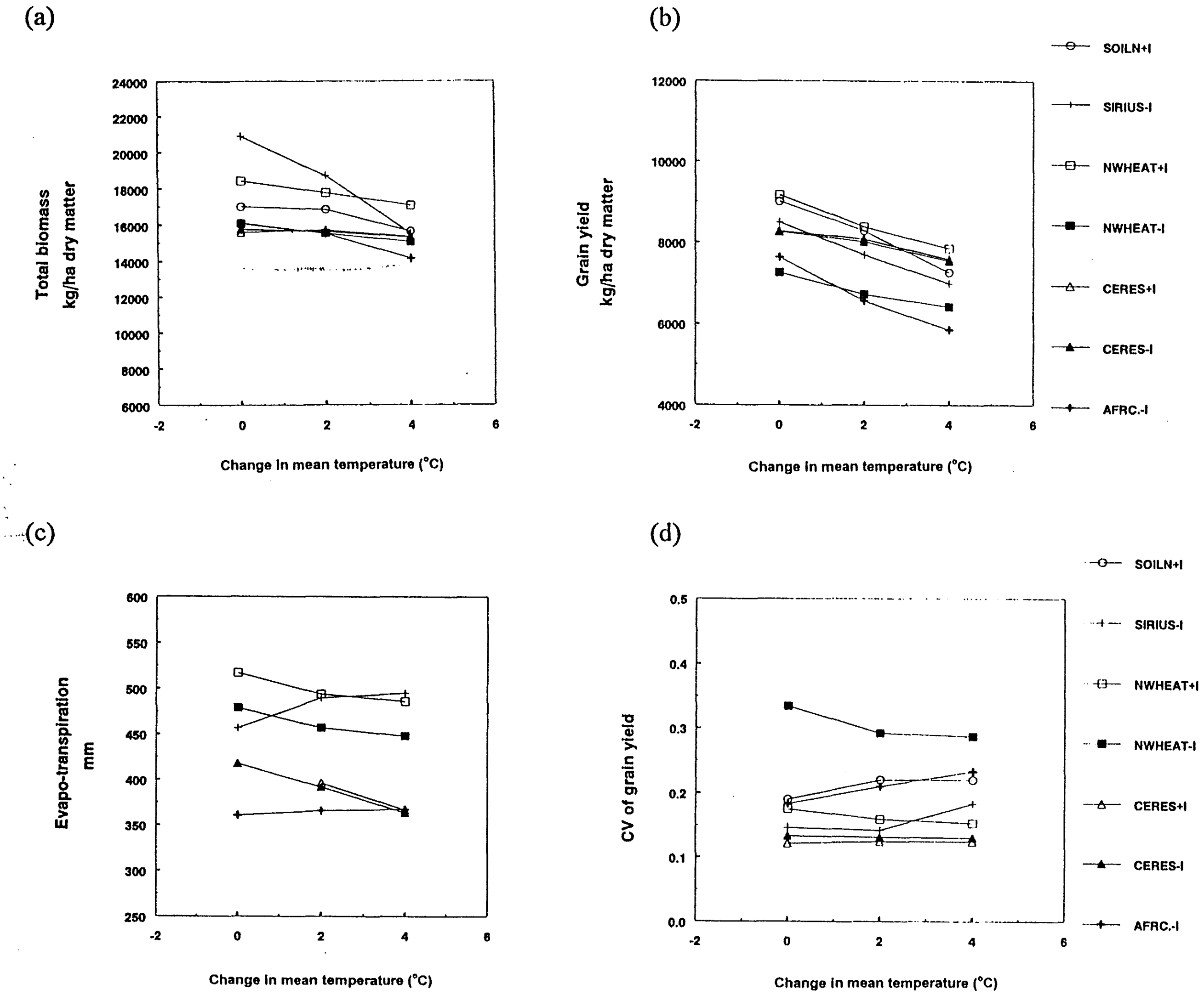


Figure 5.7.12 Sensitivity to changes in mean temperature in conjunction with a doubling of daily temperature variability of (a) total biomass (b) grain yield (c) cumulative evapotranspiration (from sowing to maturity) and (d) coefficient of variation (CV) of grain yield of winter wheat in Rothamsted, U.K. as simulated with the SOILN, SIRIUS, NWHEAT, CERES and AFRCWHEAT 3S (AFRC.) models for potential (+I) and water-limited (-I) production.

did not further reduce TB and GR in the AFRCWHEAT and SIRIUS runs but it considerably further reduced yields in the CERES and NWHEAT runs and in the SOILN run to a lesser extent (compare Figure 5.7.12a, b with 5.7.11a, b). ET increased slightly and considerably with higher temperatures in the AFRCWHEAT and SIRIUS runs respectively and decreased in the CERES and NWHEAT runs (Figure 5.7.12c). ET changed with temperature to about the same extent as in the runs without without doubled temperature variability (Figure 5.7.11c), but ET from the NWHEAT and SIRIUS runs was slightly higher than ET from the same model runs without doubled variability. CV of grain yield changed minimally with increased temperature, with a small increase in the AFRCWHEAT, SIRIUS and SOILN runs and a small decrease in the NWHEAT run (Figure 5.7.12d). Values for CV were slightly higher in all model runs including variability compared to CV in the runs without doubled temperature variability.

Doubling dry spell length gave identical values for TB, GR and ET in the SIRIUS run and slightly smaller values for TB, GR and ET in the AFRCWHEAT, CERES and NWHEAT runs (Figures 5.7.13a, b, c). This indicated that the degree of water stress had not increased much by doubling of the dry spell length. CV of grain yield was low and increased slightly by the doubling of dry spells in the AFRCWHEAT, CERES and SIRIUS runs and was much higher and increased more strongly by doubling of dry spells in the NWHEAT run, indicating a stronger yield-reducing effect of water shortage in this run (Figure 5.7.13d).

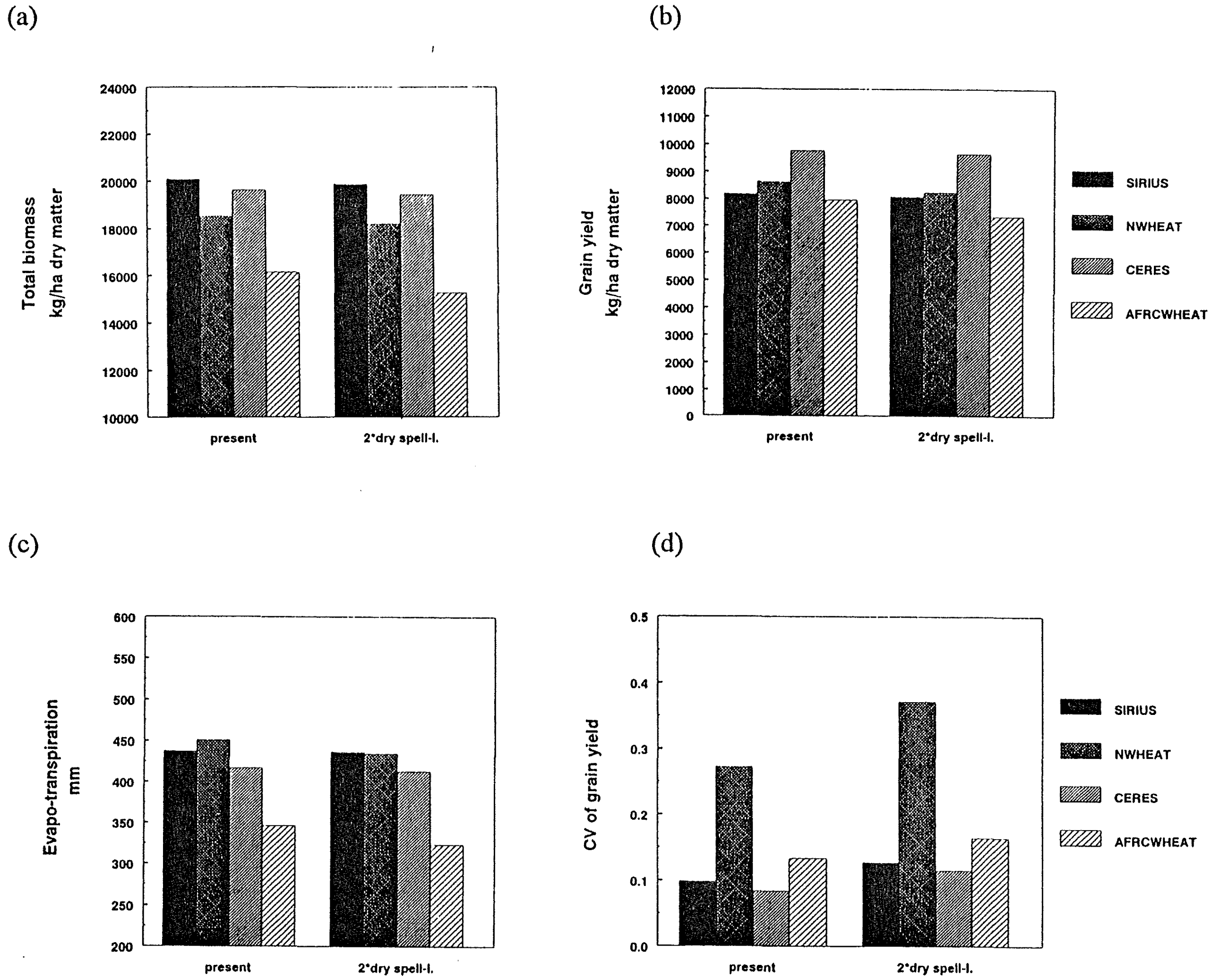


Figure 5.7.13 Sensitivity to a doubling in the length of dry spells of (a) total biomass (b) grain yield (c) cumulative evapotranspiration (from sowing to maturity) and (d) coefficient of variation (CV) of grain yield of winter wheat in Rothamsted, U.K. as simulated with the SIRIUS, NWHEAT, CERES and AFRCWHEAT 3S models for water-limited (-I) production.

5.7.5.3 *Sevilla: mean changes in climate*

Increasing the amount of rainfall at Sevilla resulted in an increase in TB and GR in most water-limited runs (Figure 5.7.14a, b). Yield increase with increasing precipitation was higher in the NWHEAT run than in the CERES and SIRIUS runs, which was indicative of the degree of water shortage. In the AFRCWHEAT run water supply did not limit crop yield. In this run ET was relatively low and increased considerably with the amount of precipitation which was contrary to expectation (Figure 5.7.14c). In the CERES, NWHEAT and SIRIUS runs ET also increased with increasing precipitation. CV of grain yield was constant and very low in the AFRCWHEAT run indicating no water shortage, and decreased rapidly in the CERES, NWHEAT and SIRIUS runs with increasing precipitation amount due to a reduced risk of water shortage (Figure 5.7.14d).

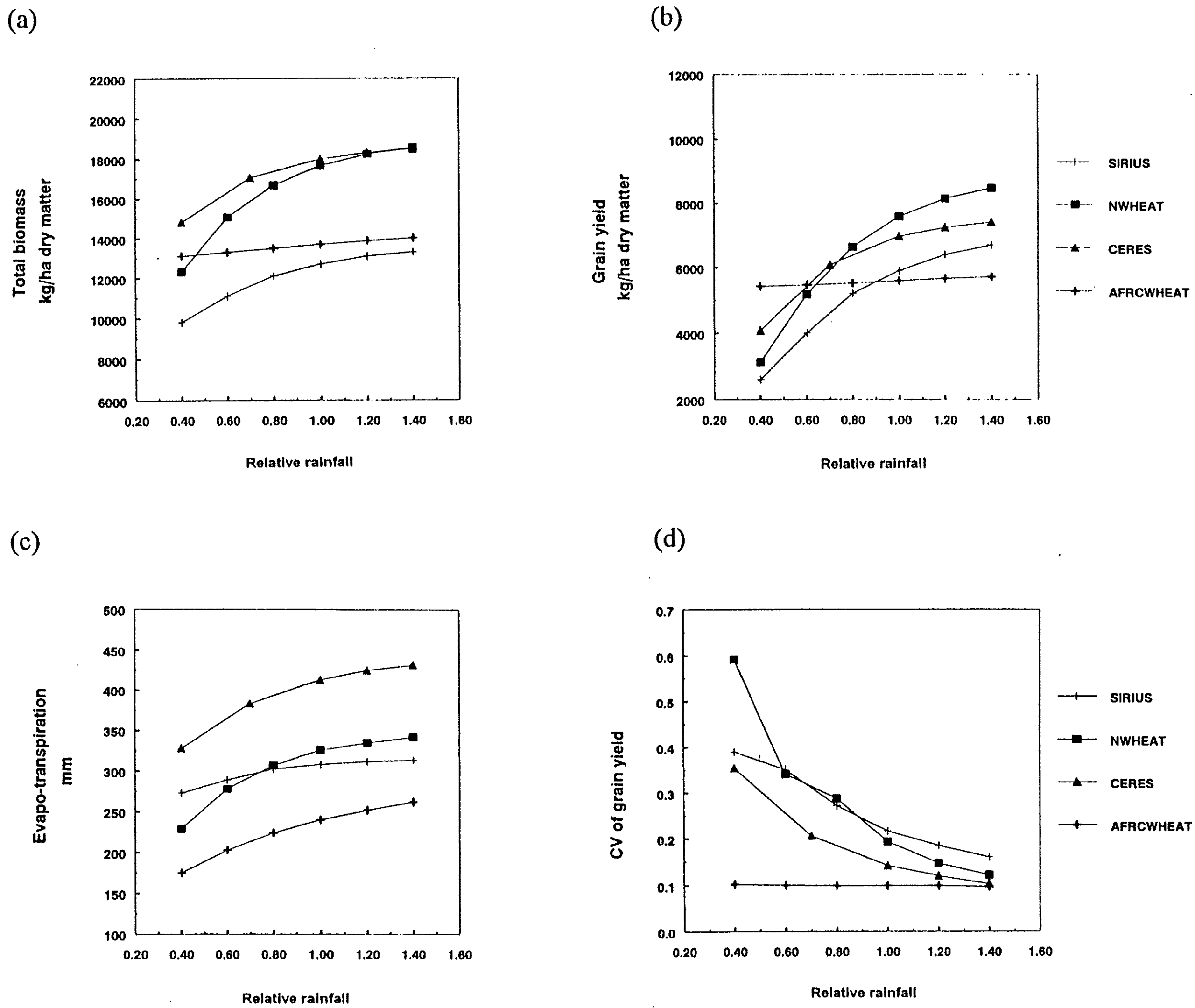


Figure 5.7.14 Sensitivity to precipitation of (a) total biomass (b) grain yield (c) cumulative evapotranspiration (from sowing to maturity) and (d) coefficient of variation (CV) of grain yield of winter wheat in Sevilla, Spain as simulated with the SIRIUS, NWHEAT, CERES and AFRCWHEAT 3S models for water-limited (-I) production.

Increasing concentrations of atmospheric CO_2 resulted in a larger increase in TB in the CERES and NWHEAT runs than in the SIRIUS and AFRCWHEAT runs. The largest relative increase in GR occurred in the NWHEAT run (Figure 5.7.15a, b). This contrasted with results for Rothamsted where the positive effect of increased CO_2 on TB was smallest in the NWHEAT run, resulting from the interaction between increased CO_2 and low temperatures. ET remained constant with increasing atmospheric CO_2 in the AFRCWHEAT and SIRIUS runs and decreased slightly in the CERES and NWHEAT runs (Figure 5.7.15c). In the AFRCWHEAT run ET is relatively low and in the CERES run ET is relatively high. CV of grain yield did not change with increasing atmospheric CO_2 except for in the CERES and NWHEAT water-limited runs (Figure 5.7.15d). In these runs water shortage reduced GR in many years resulting in a higher CV of grain yield. Increases in atmospheric CO_2 caused a decrease in ET and, hence, less GR reduction by water shortage which resulted in a lower value for CV.

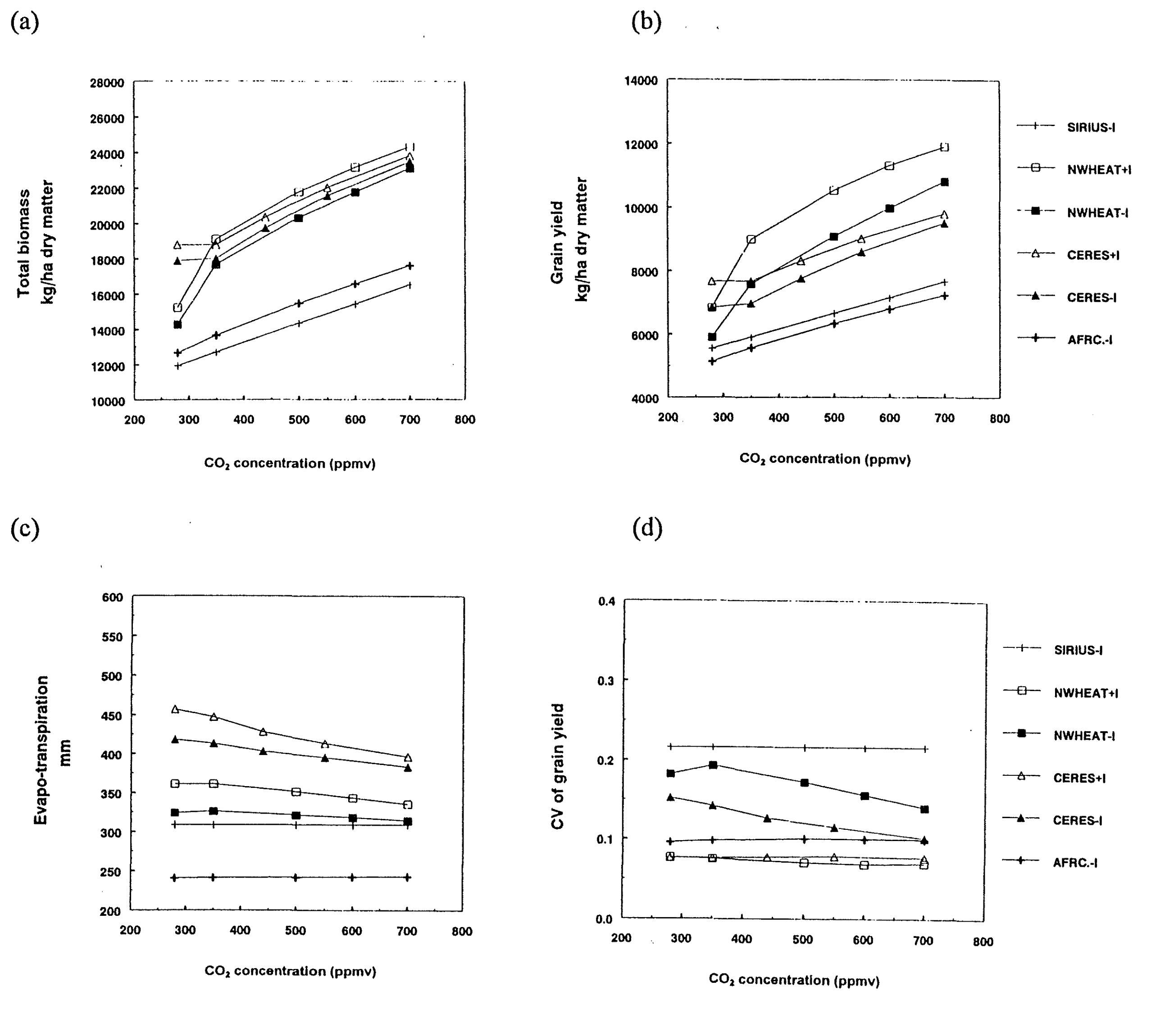


Figure 5.7.15 Sensitivity to atmospheric CO_2 concentration of (a) total biomass (b) grain yield (c) cumulative evapotranspiration (from sowing to maturity) and (d) coefficient of variation (CV) of grain yield of winter wheat in Sevilla, Spain as simulated with the SIRIUS, NWHEAT, CERES and AFRCWHEAT 3S (AFRC.) models for potential (+I) and water-limited (-I) production.

Increases in temperature resulted in a decrease in TB and GR in all model runs, mainly through advancement of the maturity date, (Figure 5.7.16a, b). SIRIUS calculated a much smaller decrease in GR with warming than the other models, and NWHEAT calculated a stronger decrease in TB. Decreases in temperature resulted in a decrease in TB in the CERES and NWHEAT water-limited runs and a decrease in GR in the CERES, NWHEAT and SIRIUS water-limited runs. This was probably due to the soil water supply which became more limiting for ET during the long period of growth at cooler temperatures (Figure 5.7.16c). ET decreased with increasing temperature, particularly when soil water supply not limiting. Only in the AFRCWHEAT run did ET not change with increasing temperature and its value was relatively low. CERES calculated the highest values for ET. This was different from results for Rothamsted where NWHEAT calculated much higher values for ET than CERES. The CV of grain yield was highest if water shortage affected crop growth relatively severely which was the case in the CERES, NWHEAT and SIRIUS water-limited runs and in particular at cooler temperatures (Figure 5.7.16d). In the AFRCWHEAT run CV of grain yield was low except with a 6°C warming where a strong increase in CV occurred.

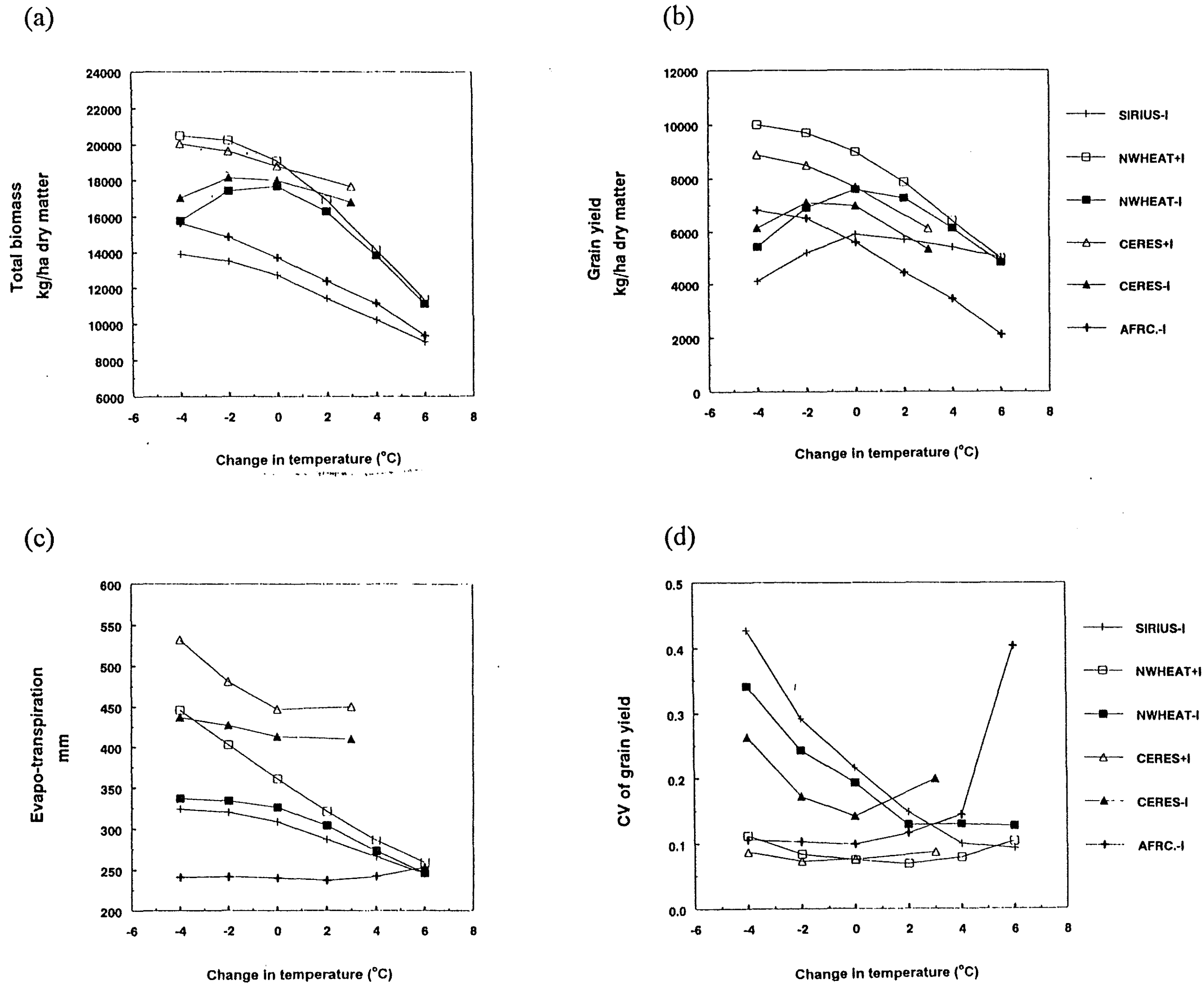


Figure 5.7.16 Sensitivity to temperature of (a) total biomass (b) grain yield (c) cumulative evapotranspiration (from sowing to maturity) and (d) coefficient of variation (CV) of grain yield of winter wheat in Sevilla, Spain as simulated with the SIRIUS, NWHEAT, CERES and AFRCWHEAT 3S (AFRC.) models for potential (+I) and water-limited (-I) production.

5.7.5.4 *Sevilla: changes in climatic variability*

Simulations have also been conducted for a doubling of daily temperature variability (in conjuction with changes in mean temperature) and a doubling of the length of dry spells. Increases in the both the mean and variability of temperature resulted in a decrease in TB and GR (Figure 5.7.17a, b). This can be explained mainly by the advanced date of maturity at higher temperatures. Exceptions were GR in the SIRIUS run and TB for a limited temperature rise (+2°C) in the AFRCWHEAT run, which slightly increased with temperature. Doubled temperature variability did not affect TB and GR in the SIRIUS run but it reduced yields considerably in the AFRCWHEAT, CERES and NWHEAT runs and in particular with cooling (compare Figure 5.7.17a, b with 5.7.16a, b). ET decreased with warming in the SIRIUS and NWHEAT runs, remained at a constant low value in the AFRCWHEAT run, and remained constant or even increased in the CERES runs (Figure 5.7.17c). ET changed only minimally with doubled temperature variability compared to values calculated without variability (Figure 5.7.16c).

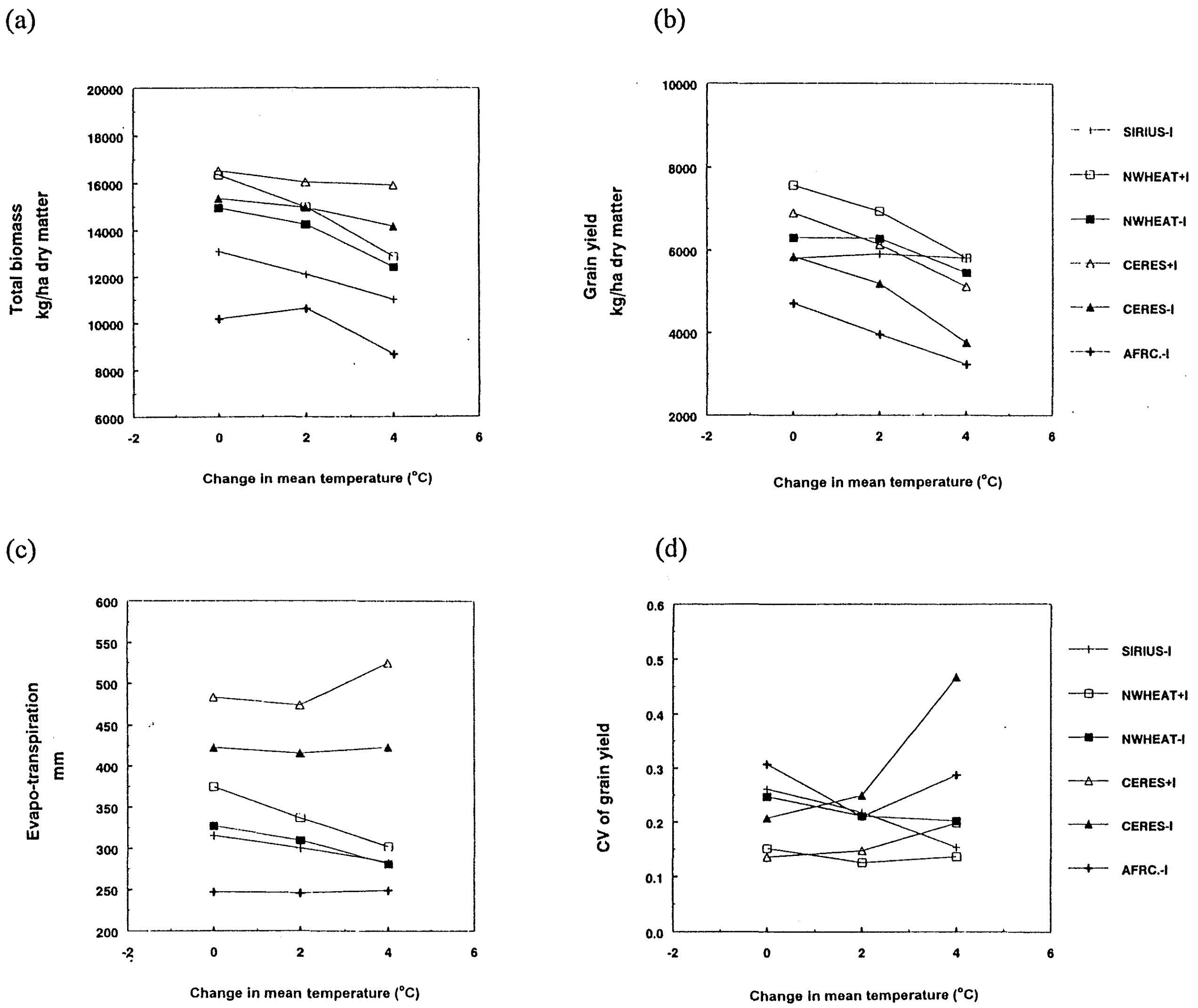


Figure 5.7.17 Sensitivity to changes in mean temperature in conjunction with a doubling of daily temperature variability (a) total biomass (b) grain yield (c) cumulative evapotranspiration (from sowing to maturity) and (d) coefficient of variation (CV) of grain yield of winter wheat in Sevilla, Spain as simulated with the SIRIUS, NWHEAT, CERES and AFRCWHEAT 3S (AFRC.) models for potential (+I) and water-limited (-I) production.

CV of grain yield showed little sensitivity to warming in NWHEAT potential production run, decreased slightly and moderately with warming in the NWHEAT and SIRIUS water-limited runs respectively, was rather variable in the AFRCWHEAT run and increased moderately and strongly in both CERES runs (potential and water-limited) (Figure 5.7.17d). CV of grain yield was slightly to moderately higher with doubled temperature variability than without (Figure 5.7.16d).

Doubling the length of dry spells resulted in lower TB and much lower GR in the CERES, NWHEAT and SIRIUS water-limited runs (Figure 5.7.18a, b). This can largely be explained by the cumulative amount of precipitation during the growth period which was approximately halved by doubling dry spell length. In the AFRCWHEAT run, however, the yield remained the same with doubling of dry spells indicating that water supply was not limiting. In this run, however, ET decreased strongly with doubling

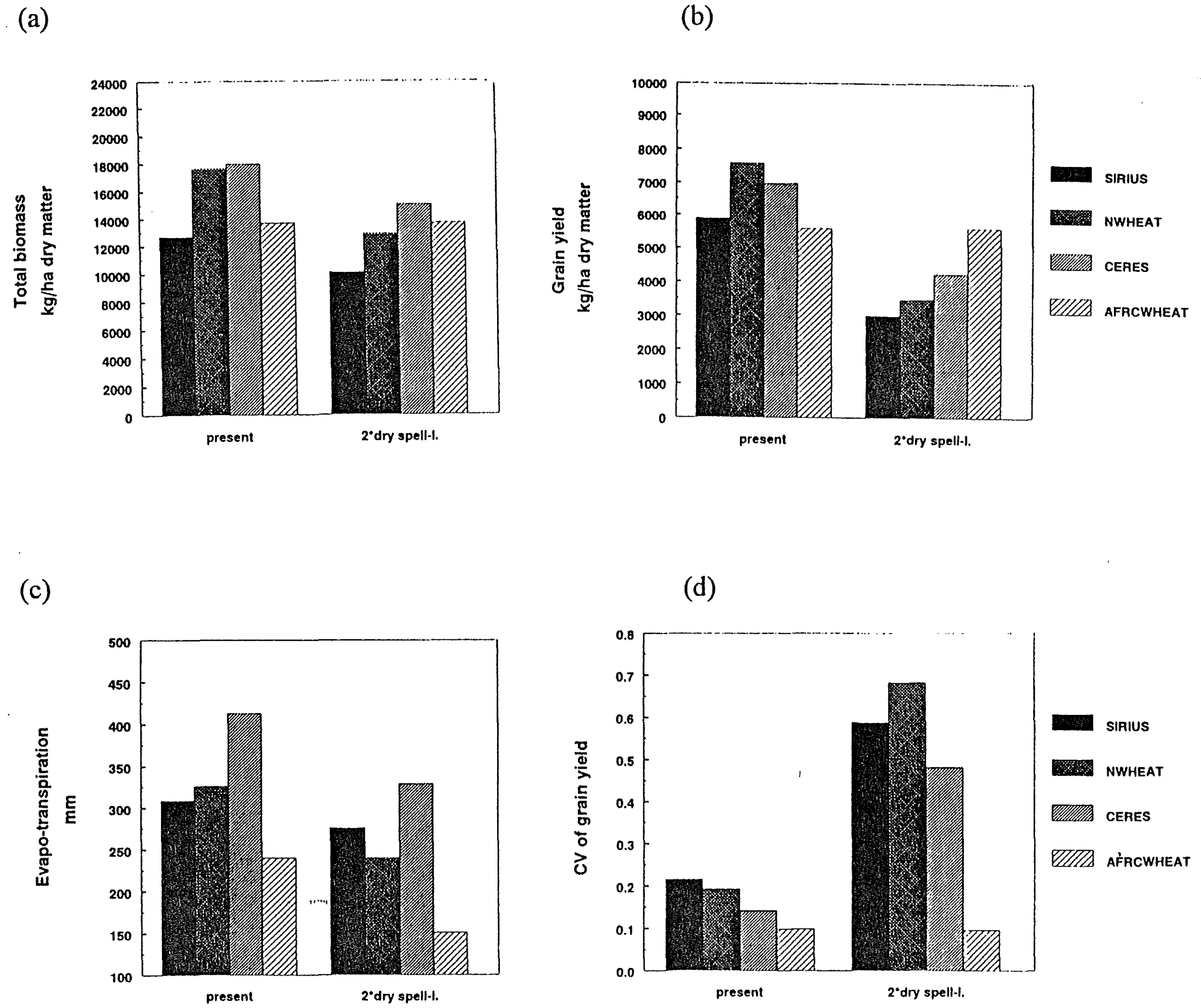


Figure 5.7.18 Sensitivity to a doubling in the length of dry spells of (a) total biomass (b) grain yield (c) cumulative evapotranspiration (from sowing to maturity) and (d) coefficient of variation (CV) of grain yield of winter wheat in Sevilla, Spain as simulated with the SIRIUS, NWHEAT, CERES and AFRCWHEAT 3S models for water-limited production.

of dry spells (Figure 5.7.18c). The reason for this is not known. In the other model runs, ET also decreased with doubling of dry spells as a result of the more limited water supply. CV of grain yield increased strongly with doubling of dry spells in the CERES, NWHEAT and SIRIUS runs, which indicated the strongly increasing risk of yield reduction by water shortage (Figure 5.7.18d). In the AFRCWHEAT run CV of grain yield was low and did not change.

5.7.6 Application of the climate change scenarios

Models have been applied for both current and future climatic conditions at Rothamsted and Sevilla. Future climate data sets for time periods of 30 years have been produced with the LARS-WG stochastic weather generator (Racsko *et al.*, 1991; Barrow and Semenov, 1995) on the basis of output from GCM experiments. Output from two types of GCM models have been used: (i) equilibrium 2xCO_2 models (UKLO and UKHI); and (ii) transient models (UKTR and GFDL). Two types of scenarios have been constructed on the basis of output from the GCM experiments: (i) scenarios containing monthly mean changes in weather variables only; and (ii) scenarios which include changes in variability, as well as the same monthly mean changes, in weather variables. Scenarios which include changes in climatic variability are denoted by 'V' following the GCM name, eg. UKHIV.

GCM results used for these analyses were those from the UK Met. Office equilibrium low resolution experiment without changes in variability (UKLO), the UK Met. Office equilibrium high resolution experiment, both without (UKHI) and with changed variability (UKHIV), the UK Met. Office transient GCM experiment, both without (UKTR) and with changed variability (UKTRV), and the Geophysical Fluid Dynamics Laboratory transient GCM experiment without changes in variability (GFDL). Calculations were performed mainly for the scenario climate with the corresponding increased level of atmospheric CO_2. From both transient experiments results of two decades have been used, i.e. UKTR decades 31-40 and 66-75, and GFDL decades 25-34 and 55-64. For each of these experiments, the scenario for the earlier decade was applied together with a concentration of atmospheric CO_2 of 454 ppmv CO_2 and that for the second decade with 617 ppmv CO_2. These concentrations correspond to the IPCC IS92a emissions scenario. For the equilibrium scenarios (UKLO and UKHI) the CO_2 concentration was set at 560 ppmv. For more information on the construction of the climate change scenarios and how these GCM and emissions scenarios relate to actual years see Section 2.4.

A higher atmospheric CO_2 concentration resulted in an increase in the CO_2 assimilation rate and in a slight decrease in the transpiration rate in most model runs (see Section 5.7.5). In order to analyse the impact of climate change independent from the direct effect of increased atmospheric CO_2, the model runs for the UKTR scenarios for Rothamsted have been conducted for both present atmospheric CO_2 (353 ppmv) and increased CO_2 concentrations.

Not all models have been applied to all situations and sites. SOILN has been run for the scenarios at Rothamsted and for potential production only. The other models have been used for both sites. CERES and NWHEAT have calculated both potential and water-limited crop yields, whilst AFRCWHEAT and SIRIUS have calculated only water-limited crop yields. Results shown are the mean output of 30 years of crop growth simulations.

5.7.6.1 *Rothamsted: Equilibrium scenarios*

Grain yield: Potential production

The UKLO scenario resulted in a lower GR in the SOILN and NWHEAT runs but not in the CERES run, compared to GR at present (Figure 5.7.19a). The UKHI scenario gave a higher GR in the SOILN and NWHEAT runs but not in the CERES run, compared to the UKLO results. If climate variability has been changed in the UKHI scenario (UKHIV), this gave the same GR in CERES and SOILN runs and a lower GR in the NWHEAT run.

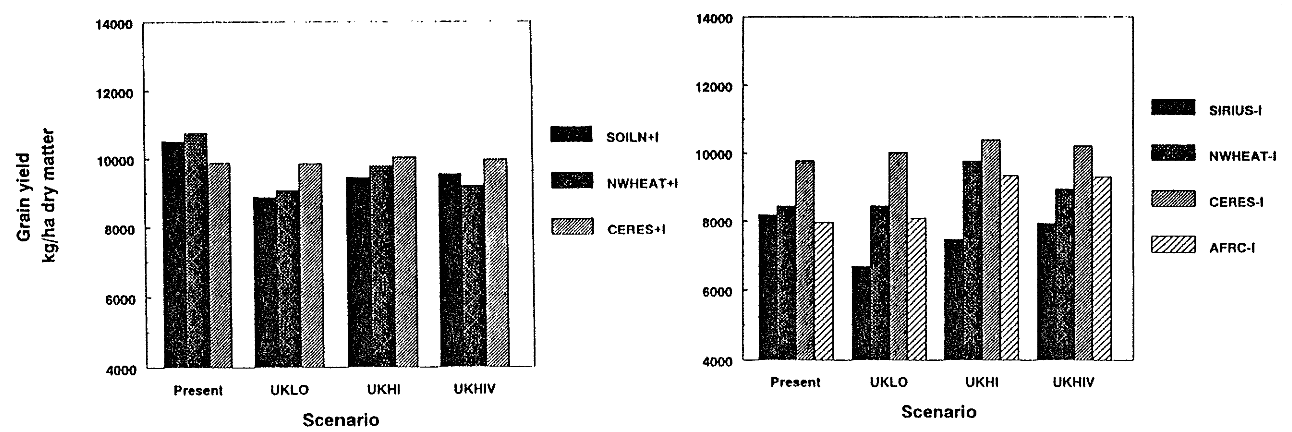
Grain yield: Water-limited production

The UKLO scenario resulted in a lower GR in the SIRIUS run, the same GR in the NWHEAT and AFRCWHEAT runs and a slightly higher GR in the CERES run, compared to GR at present (Figure 5.7.19a). The UKHI scenario gave a higher GR in all runs, compared to UKLO results, and also higher than GR at present, except for the SIRIUS run. Changed variability in the UKHI scenario (UKHIV) gave lower GR in the NWHEAT run, the same GR in CERES and AFRCWHEAT runs, and a slightly higher GR in the SIRIUS run.

CV of grain yield

CV of grain yield was slightly higher in all equilibrium scenarios, compared, with present, in the CERES and SOILN potential production runs and remained the same in the NWHEAT potential production run (Figure 5.7.19b). In the

(a)



(b)

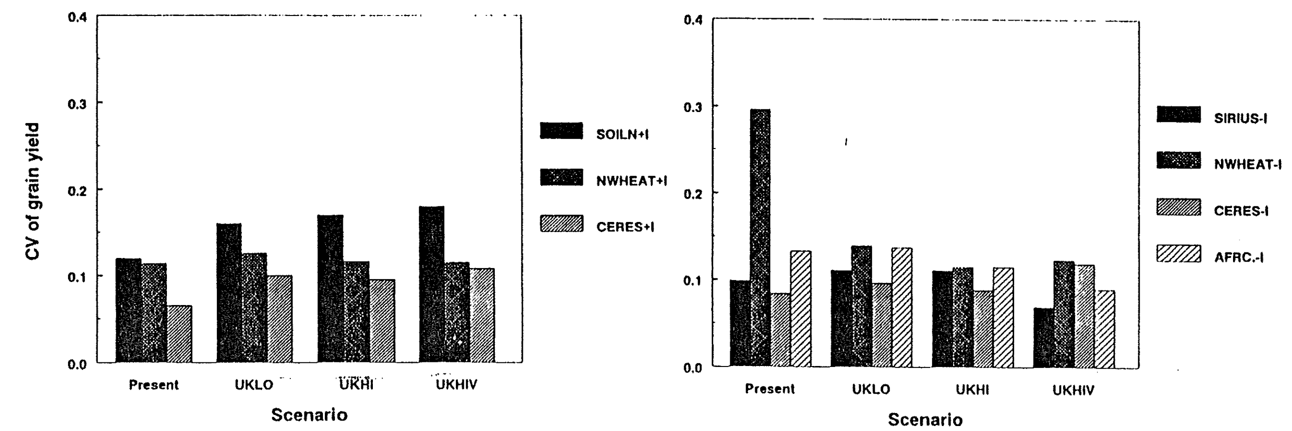


Figure 5.7.19 (a) Average value and (b) coefficient of variation (CV) of grain yield of winter wheat at present and future climatic conditions (including the direct effects of increasing atmospheric CO_2) in Rothamsted, U.K. as simulated with the SOILN, SIRIUS, NWHEAT, CERES and AFRCWHEAT 3S (AFRC.) models for potential (+I) and water-limited (-I) production. 'V' denotes scenarios which include changed variability.

water-limited runs, the UKLO and UKHI scenarios resulted in about the same CV of grain yield as present. Only in the NWHEAT run was the CV of grain yield lower than at present, indicating a decrease in the risk of water shortage in the future. With changed climate variability in the UKHI scenario (UKHIV), CV of grain yield decreased in the SIRIUS and AFRCWHEAT runs. However, it remained almost the same and slightly increased in the NWHEAT and CERES water-limited runs, respectively.

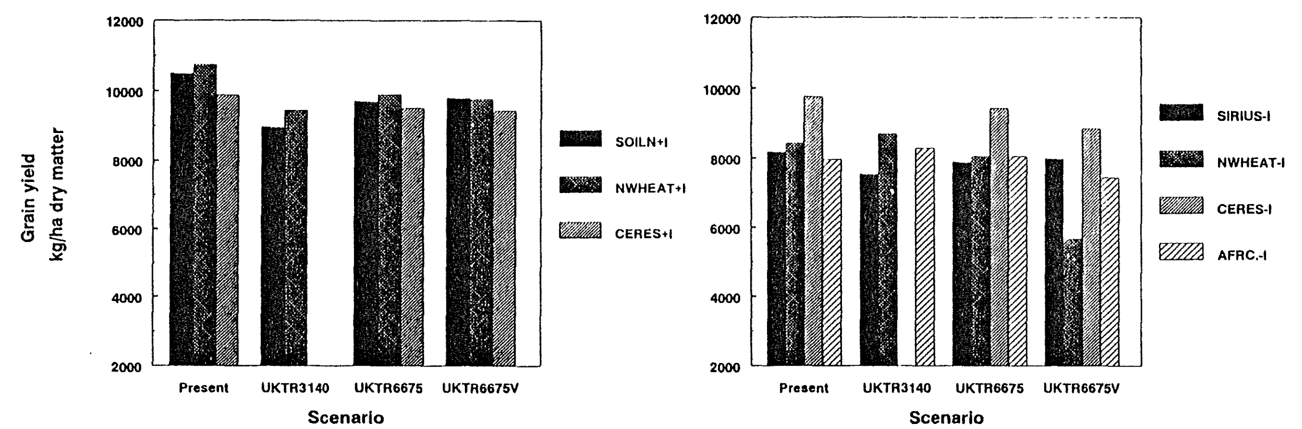
5.7.6.2 *Rothamsted: Transient scenarios*

UKTR scenario without direct CO_2 effect

Grain yield: Potential production

The UKTR3140 and UKTR6675 scenarios gave moderately and slightly lower GR, respectively (Figure 5.7.20a). All model runs gave similar results. With changed climatic variability (UKTR6675V scenario) GR remained similar.

(a)



(b)

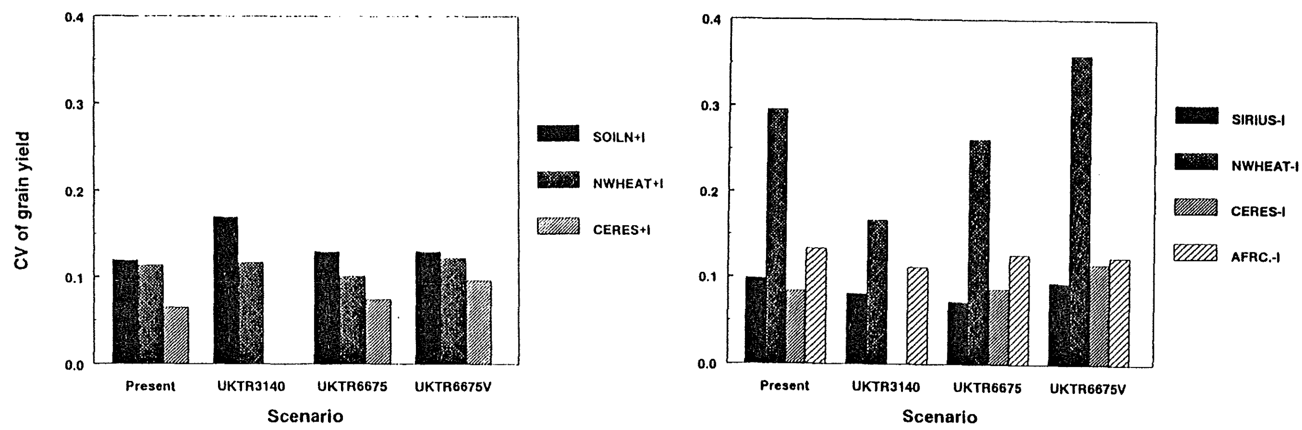


Figure 5.7.20 (a) Average value and (b) coefficient of variation (CV) of grain yield of winter wheat at present and future climatic conditions (not including the direct effects of increasing atmospheric CO_2) in Rothamsted, U.K. as simulated with the SOILN, SIRIUS, NWHEAT, CERES and AFRCWHEAT 3S (AFRC.) models for potential (+I) and water-limited (-I) production. 'V' denotes scenarios which include changed variability.

Grain yield: Water-limited production

For the UKTR3140 scenario GR decreased in the SIRIUS run and increased in the NWHEAT and AFRCWHEAT runs, whilst for the UKTR6675 scenario GR remained similar in all model runs, compared to GR at present (Figure 5.7.20a). With changed climatic variability (UKTR6675V scenario) GR in the SIRIUS run remained almost the same and decreased slightly in the CERES and AFRCWHEAT runs and strongly in the NWHEAT run. These differences in the magnitude of the decrease in GR were caused by different degrees of change in water limitation.

CV of grain yield

CV of potential grain yield was similar to present for all scenarios and increased only marginally with changed climatic variability (Figure 5.7.20b). Only the SOILN model calculated a higher CV than present for the UKTR3140 scenario. In the water-limited situation, CV of grain yield was low in the SIRIUS and CERES runs and did not change with climate change, indicating that water supply was not limiting for crop growth. In the AFRCWHEAT run, CV of grain yield was slightly higher than in the SIRIUS and CERES runs, but did not differ from CV at present for the various scenarios. In the NWHEAT water-limited run, the present CV of grain yield was high and CV was similar for the UKTR6675 scenario, but much lower for the UKTR3140 scenario. With changed climatic variability in the UKTR6675V scenario, CV of grain yield increased slightly in the SIRIUS and CERES runs, increased considerably in the NWHEAT run, and remained the same in the AFRCWHEAT run.

UKTR scenario with direct CO_2 effect

Grain yield: Potential production

The UKTR6675 scenario including the direct effect of increased atmospheric CO_2 resulted in a considerable increase in GR, with the smallest increase occurring in the NWHEAT run (Figure 5.7.21a). Changed climatic variability did not change GR in the different runs. For the UKTR3140 scenario, GR was the same as GR at present in the CERES runs and smaller in the SOILN and NWHEAT runs.

Grain yield: Water-limited production

The UKTR6675 scenario gave a considerable increase in GR compared to GR at present (Figure 5.7.21a). If the direct effects of increased atmospheric CO_2 were not taken into account in the UKTR6675 scenario, GR generally remained similar to GR at present (Figure 5.7.20a). This indicated the strong contribution of CO_2 enrichment to the increase in GR. Changed climatic variability in the UKTR6675V scenario resulted in the same GR in the SIRIUS run, a slightly lower GR in the CERES run, and a much lower GR in the NWHEAT and AFRCWHEAT runs. For the UKTR3140 scenario GR was the same as GR at present in the SIRIUS run, slightly higher in the CERES run, and much higher in the NWHEAT and AFRCWHEAT runs.

CV of grain yield

CV of potential grain yield was virtually unchanged in the UKTR3140 and UKTR6675 scenarios, compared to CV at present (Figure 5.7.21b). Also with changed climatic variability in the UKTR6675V scenario, CV of grain yield did not increase in these runs. Only in the SOILN run did the UKTR3140 scenario result in a moderately higher value for CV. In the water-limited runs, the UKTR6675 scenario resulted in about the same CV of grain yield as at present in the CERES and AFRCWHEAT runs, and a slightly and moderately lower value for CV in the SIRIUS and NWHEAT runs, respectively. For the UKTR3140 scenario, the decreases in CV were similar or slightly larger. In the NWHEAT water-limited runs, CV of grain yield was much higher than other models, which indicated a higher degree of water shortage. With changed climatic variability in the UKTR6675V scenario CV of grain yield increased slightly in the different water-limited runs.

GFDL scenario with direct CO_2 effect

Grain yield

The GFDL2534 scenario resulted in a slight decrease in GR in the NWHEAT potential and

SIRIUS water-limited runs and in slight and moderate increases in the AFRCWHEAT and NWHEAT water-limited runs respectively. The GFDL5564 scenario resulted in moderate increases in GR in the NWHEAT potential, CERES potential, SIRIUS and CERES water-limited runs and in strong increases in the AFRCWHEAT and NWHEAT water-limited runs (Figure 5.7.22a).

CV of grain yield

For the GFDL scenarios CV of grain yield in the potential runs was the same or slightly lower than that at present (Figure 5.7.22b). In the water-limited situation the GFDL2534 scenario resulted in the same, slightly lower and much lower values for CV of grain yield in the AFRCWHEAT, SIRIUS and NWHEAT water-

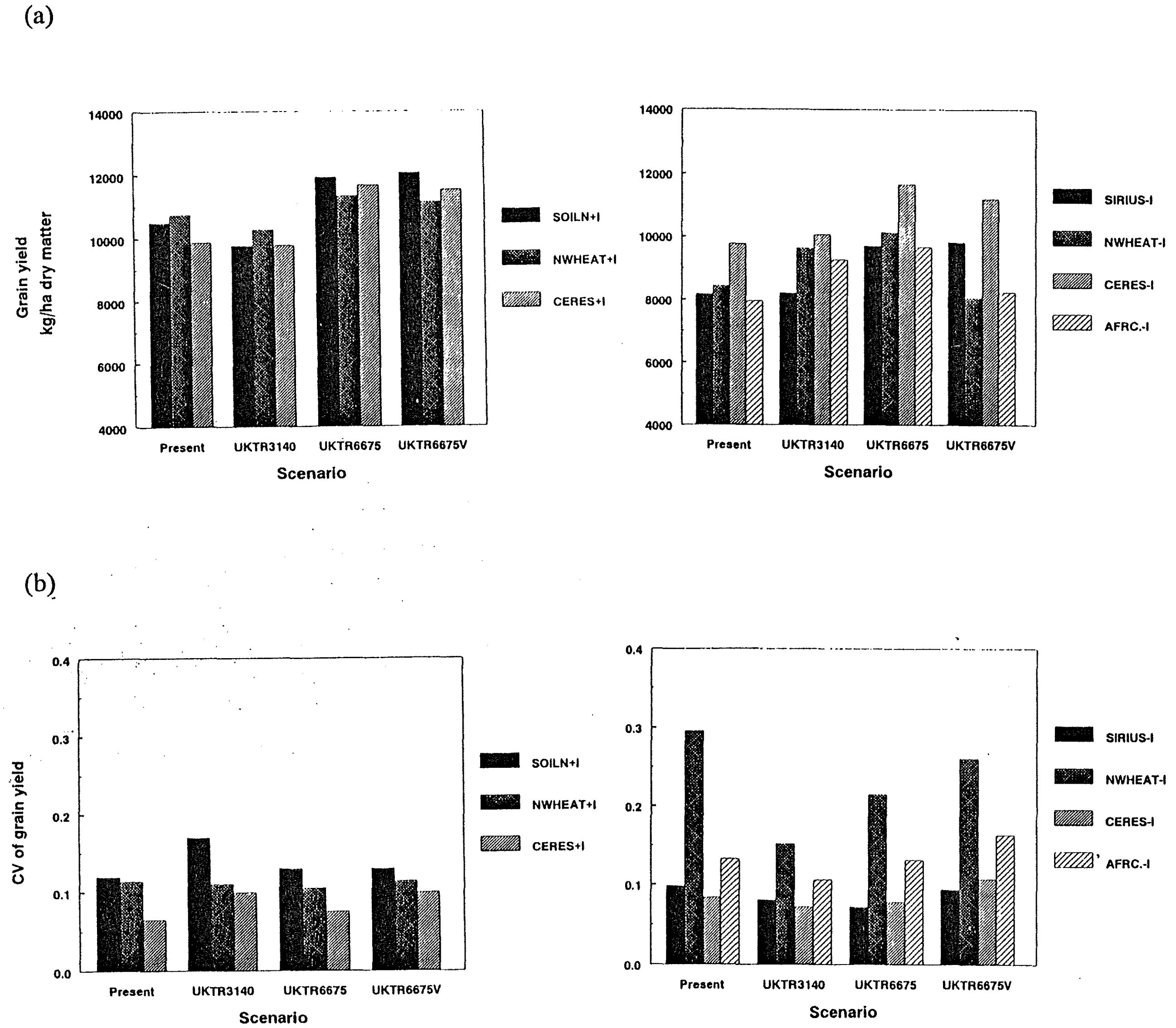


Figure 5.7.21 (a) Average value and (b) coefficient of variation (CV) of grain yield of winter wheat at present and future climatic conditions (including the direct effects of increasing atmospheric CO_2) in Rothamsted, U.K. as simulated with the SIRIUS, NWHEAT, CERES and AFRCWHEAT 3S (AFRC.) models for potential (+I) and water-limited (-I) production. 'V' denotes scenarios which include changed variability.

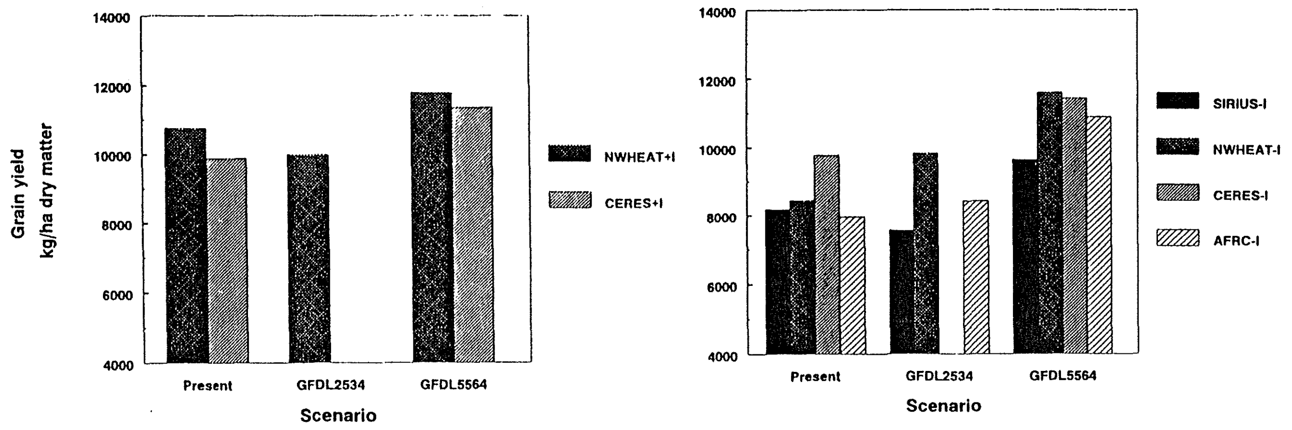
limited runs respectively, whilst the GFDL5564 scenario resulted in a slightly higher value for CV of grain yield in the CERES water-limited run, a slightly lower value in the AFRCWHEAT and SIRIUS runs, and a much lower value in the NWHEAT water-limited run, all values compared to those at present. The low values of CV of grain yield and the high GR in the water-limited runs indicated that the risk of water shortage and GR reduction by water stress was very low in the GFDL scenario climate.

5.7.6.3 *Sevilla: Equilibrium scenarios*

Grain yield

The UKLO scenario resulted in similar values for GR in the CERES potential and the SIRIUS and NWHEAT water-limited runs, slightly higher GR in the CERES water-limited run, and in slightly and moderately lower GR in the AFRCWHEAT and the NWHEAT potential water-limited runs respectively, compared to GR at present (Figure

(a)



(b)

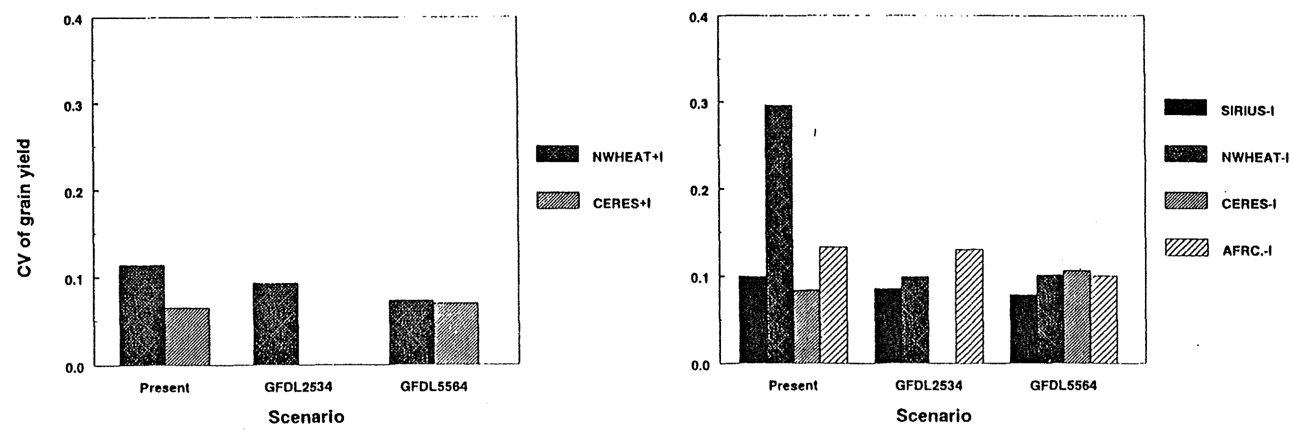


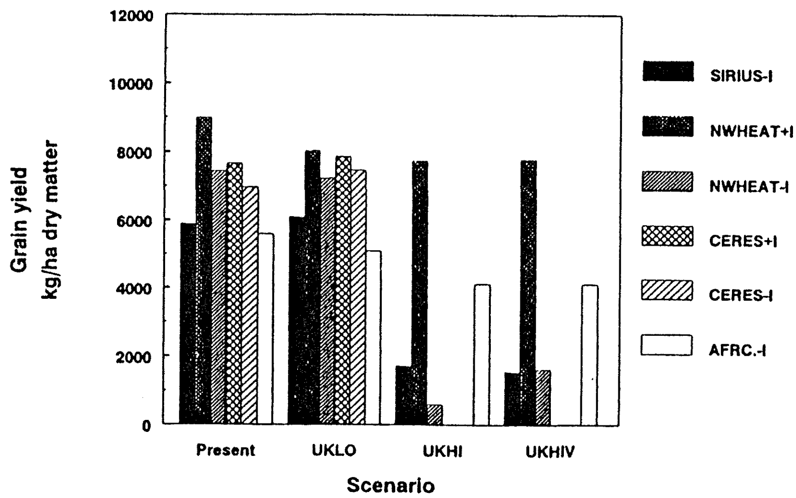
Figure 5.7.22 (a) Average value and (b) coefficient of variation (CV) of grain yield of winter wheat at present and future climatic conditions (including the direct effects of increasing atmospheric CO_2) in Rothamsted, U.K. as simulated with the SIRIUS, NWHEAT, CERES and AFRCWHEAT 3S (AFRC.) models for potential (+I) and water-limited (-I) production.

5.7.23a). The UKHI scenario gave a very low GR in the SIRIUS and NWHEAT water-limited runs, and resulted in a moderately lower GR in the AFRCWHEAT run and approximately the same GR in the NWHEAT potential run, compared to UKLO results. Changed climatic variability in the UKHIV scenario, gave almost no change in GR in all runs. In most water-limited runs the water supply in the UKHI (with and without variability) scenarios appeared to strongly limit GR, but in the present and UKLO scenario water supply was only limiting to a small extent.

CV of grain yield

For the UKLO scenario, CV of grain yield in most model runs was similar to CV at present (Figure 5.7.23b). Only the SIRIUS run gave a lower CV and the CERES water-limited run a higher CV for the UKLO scenario. The UKHI

(a)



(b)

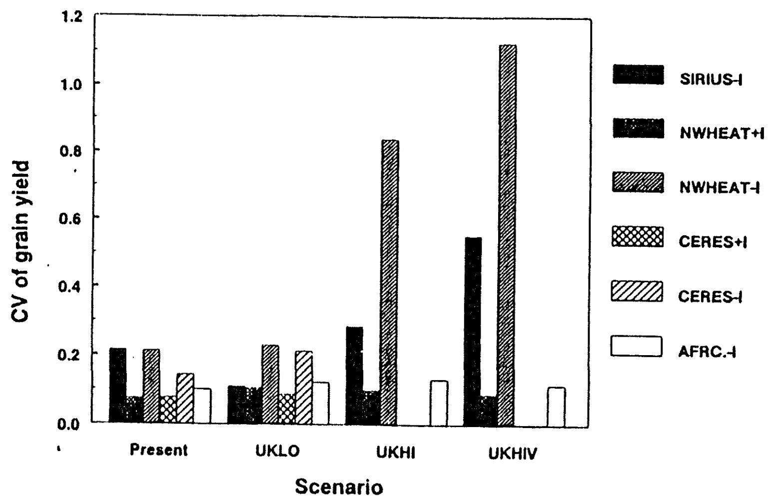


Figure 5.7.23 (a) Average value and (b) coefficient of variation (CV) of grain yield of winter wheat at present and future climatic conditions (including the direct effects of increasing atmospheric CO_2) in Sevilla, Spain as simulated with the SIRIUS, NWHEAT, CERES and AFRCWHEAT 3S (AFRC.) models for potential (+I) and water-limited (-I) production. 'V' denotes scenarios which include changed variability.

scenario produced similar CVs of grain yield in the NWHEAT potential and AFRCWHEAT water-limited runs and a moderately and much higher value for CV in the SIRIUS and NWHEAT water-limited runs respectively, compared to UKLO results. With changed climatic variability in the UKHIV scenario, the CV of grain yield remained the same in the NWHEAT potential and AFRCWHEAT water-limited runs and increased strongly in the SIRIUS and NWHEAT water-limited runs. In most water-limited runs, CV of grain yield for the UKHI (with and without variability) scenarios was much higher than both the CV at present and in the UKLO scenario. This indicated that in a situation without irrigation the risk for water shortage was highest in UKHI and UKHIV scenarios.

5.7.6.4 *Sevilla: Transient scenarios*

UKTR scenario with direct CO_2 effect

Grain yield: Potential production

The UKTR6675 scenario, including the direct effect of increased atmospheric CO_2, resulted in slight and moderate increases in GR in the CERES and NWHEAT runs respectively, compared to GR at present (Figure 5.7.24a). Changed climatic variability in the UKTR6675V scenario had virtually no effect on GR in both model runs. For the UKTR3140 scenario, GR was similar to GR at present in the CERES run, and slightly higher in the NWHEAT run.

Grain yield: Water-limited production

The UKTR6675 scenario gave no change in GR in the AFRCWHEAT run and slight, moderate and strong increases in GR in the CERES, SIRIUS and NWHEAT runs respectively, compared to GR at present. Changed climatic variability in the UKTR6675V scenario resulted in the same GR in the AFRCWHEAT run, a considerably lower GR in the CERES run and a much lower GR in the SIRIUS and NWHEAT runs. For UKTR3140 scenario, GR was approximately the same as GR at present in all water-limited runs.

CV of grain yield

The UKTR3140 and UKTR6675 scenarios gave almost no change in CV of grain yield in the potential runs (Figure 5.7.24b). Also changed climatic variability in the UKTR6675V scenario did not increase CV of grain yield in these runs. In the water-limited situation, the UKTR6675 scenario resulted in almost the same CV of grain yield as CV at present in the AFRCWHEAT run and a slightly and moderately lower value for CV in the CERES and the SIRIUS and NWHEAT runs respectively. The UKTR3140 scenario gave an increase in CV of grain yield in the SIRIUS and NWHEAT water-limited runs and no change in CV in the AFRCWHEAT and CERES water-limited runs, compared to CV at present. With changed climatic variability in the UKTR6675V scenario, CV of grain yield remained the same in the AFRCWHEAT run, increased strongly in the SIRIUS and CERES water-limited runs and very strongly in the NWHEAT water-limited run. CV of grain yield remained low if the degree of water limitation during crop growth was small, such as in the AFRCWHEAT runs.

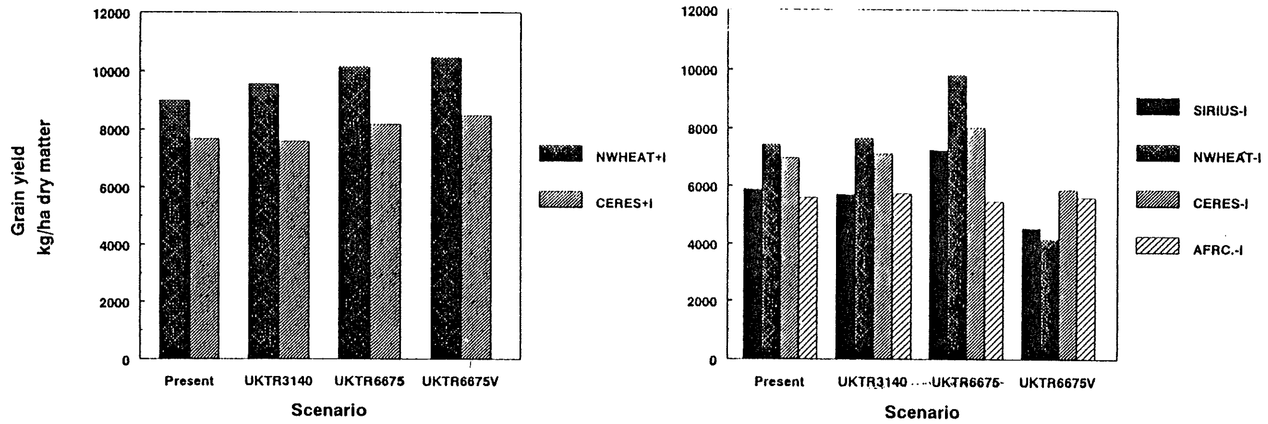
The UKTR6675 scenario resulted in higher values for GR and lower values for CV of grain yield in all water-limited runs, except AFRCWHEAT (which showed little sensitivity to water shortage) (Figure 5.7.24). Changed climatic variability in the UKTR6675V scenario resulted in much lower GR and much higher CV of grain yield in all water-limited runs, except AFRCWHEAT. For a more detailed analysis, cumulative probability functions of GR in the SIRIUS and NWHEAT water-limited runs for the UKTR6675 (with and without variability) scenarios are presented in Figure 5.7.25. These functions show that with changed climatic variability the distribution of GR has been split with approximately 50% probability of a very low GR and 50% probability of GR comparable with GR calculated for the UKTR6675 scenario without changed variability.

GFDL scenario with direct CO_2 effect

Grain yield

The GFDL2534 scenario resulted in about the same GR in the SIRIUS and NWHEAT water-

(a)



(b)

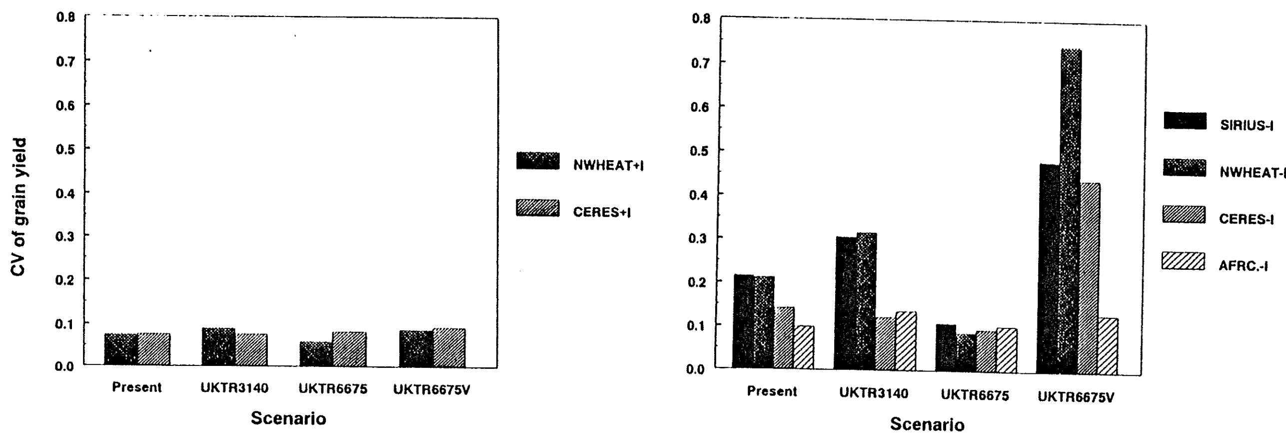


Figure 5.7.24 (a) Average value and (b) coefficient of variation (CV) of grain yield of winter wheat at present and future climate conditions (including the direct effects of increasing atmospheric CO_2) in Sevilla, Spain as simulated with the SIRIUS, NWHEAT, CERES and AFRCWHEAT 3S (AFRC.) models for potential (+I) and water-limited (-I) production. 'V' denotes scenarios include changed variability.

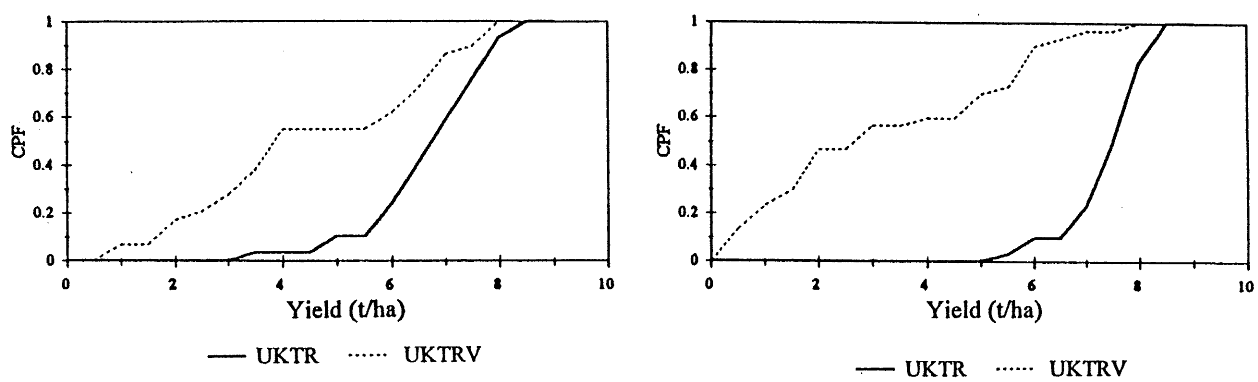


Figure 5.7.25 Cumulative probability function for grain yield of winter wheat at future climatic conditions in Sevilla, Spain as simulated with the (a) SIRIUS and (b) NWHEAT models for water-limited production. 'V' denotes scenarios which include changed variability.

limited runs and a slight and a moderate increase in the AFRCWHEAT water-limited and NWHEAT potential runs respectively (Figure 5.7.26a). The GFDL5564 scenario gave a slight increase in GR in the AFRCWHEAT water-limited and the CERES potential and water-limited runs and a moderate increase in the SIRIUS water-limited and the NWHEAT potential and water-limited runs, all compared to GR at present. GR was relatively high in the NWHEAT runs and relatively low in the AFRCWHEAT and SIRIUS runs.

CV of grain yield

For the GFDL2534 scenario CV of grain yield was slightly higher in NWHEAT potential and AFRCWHEAT water-limited runs and moderately higher in the SIRIUS and NWHEAT water-limited runs (Figure 5.7.26b). For the GFDL5564 scenario CV was slightly higher in the AFRCWHEAT water-limited run, remained the same in the CERES and NWHEAT potential runs, was slightly lower in the SIRIUS and CERES water-limited runs and moderately lower in the NWHEAT water-limited run, all compared to CV at present. The relatively high values for CV of grain yield in water-limited runs for the GFDL2534 scenario indicated an increased risk for water shortage and yield reduction. For the GFDL5564 scenario the opposite was found.

5.7.7 Discussion

To analyse the main differences between the models and the consequences for their use in climate change studies, the following procedure was applied. Firstly, the wheat growth models compared in this study were calibrated and validated against two field data sets. This was done for Rothamsted and Sevilla, sites which can be considered representative for temperate and Mediterranean climatic zones, respectively. This enabled the ability of each model to simulate observed data from field experiments to be examined. Subsequently, for the same sites, sensitivity analyses of wheat growth and yield to changes in weather variables were carried out with the different models. This revealed correspondences and differences between the models' sensitivity. The models were then run for future climatic conditions, using various climate change scenarios for both sites. Finally, the relative importance of changes in climatic variability, compared to changes in mean values, was assessed in the sensitivity analyses and in the climate change scenarios.

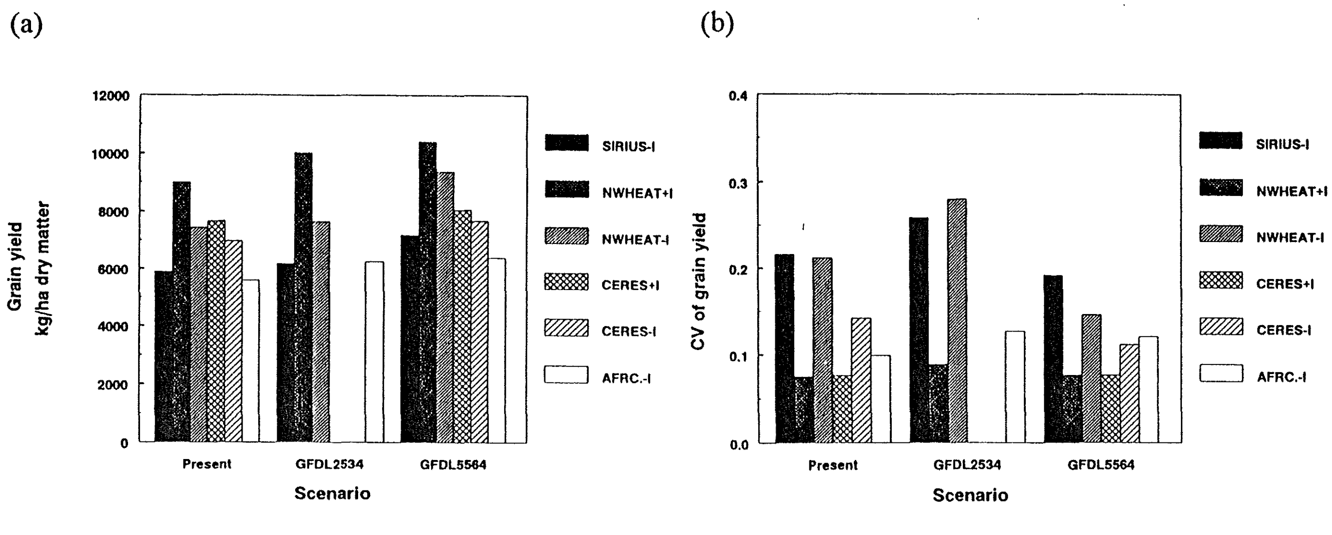


Figure 5.7.26 (a) Average value and (b) coefficient of variation (CV) of grain yield of winter wheat at present and future climatic conditions (including the direct effects of increasing atmospheric CO_2) in Sevilla, Spain as simulated with the SIRIUS, NWHEAT, CERES and AFRCWHEAT 3S (AFRC.) models for potential (+I) and water-limited (-I) production.

The simulated values for TB and GR were quite close to observed values in the irrigated calibration trial at Rothamsted. Only SIRIUS calculated a rather low value for GR. The time course of TB was calibrated quite well in most models, except for the fact that the growth in spring was overestimated strongly in the SIRIUS run and moderately in the CERES run. The time course of LAI was simulated quite well by AFRCWHEAT and SOILN but not correctly by the other models. ET was simulated quite accurately by the different models and also NB was simulated quite well. AFRCWHEAT, and SOILN to a lesser extent, underestimated the total available amount of nitrogen which resulted in a reduction of nitrogen uptake at the end of the growth period. In the CERES run, the overestimated growth in spring resulted in a too rapid nitrogen uptake in spring but NB at maturity corresponded well to the observed value.

Results from the second irrigated trial at Rothamsted were used to validate the models. The simulated and observed dates of anthesis corresponded reasonably well in the different model runs. The date of maturity was only calculated well in the CERES and SIRIUS runs. The date of maturity in the AFRCWHEAT and NWHEAT runs was a week later than the observed date, which was partly a result of the phenology routine in the models and partly an experimental artefact. SOILN needed a second calibration of phenological development. Simulated TB and GR were high compared to those in the field trial, except those modelled with SOILN. The time course of TB was simulated reasonably by AFRCWHEAT, NWHEAT and SOILN up to 40 days before the date of maturity when the observed growth curve started to flatten off. This part of the curve was only simulated well by SOILN. Growth in spring was again overestimated strongly and moderately by SIRIUS and CERES, respectively. The time course of LAI was simulated well by SOILN only. ET was simulated quite accurately by the different models. The course of NB was simulated reasonably well by AFRCWHEAT, NWHEAT and SOILN up to day 150. From that date the rate of nitrogen uptake in the field trial became very small because of depletion of the soil nitrogen supply. This was only simulated well by AFRCWHEAT and SOILN.

For Sevilla only GR from variety trials was available. Results from simulations of water-limited wheat growth could be compared, but a thorough calibration and validation was not possible. The highest value for TB was calculated with NWHEAT, intermediate values with CERES and SIRIUS, and the lowest value with AFRCWHEAT. The time course of TB was almost identical in both NWHEAT and CERES runs, except for the fact that CERES simulated a curve that flattened off at an earlier date. SIRIUS calculated a smaller rate of growth during the main growth period than the other models. In the AFRCWHEAT run the increase in TB started at a later date and stopped at an earlier date than the other models. The time course of LAI as calculated with the different models was similar to values simulated for the field trials at Rothamsted. In the SIRIUS and CERES runs ET during the initial part of the growth period was relatively high which can be explained from the high values for LAI. During the rest of the growth period these models calculated the same increase in ET as NWHEAT. In the AFRCWHEAT run ET was much smaller, probably because in this model the soil water supply was more limiting. Nitrogen uptake started relatively early in the CERES run which was partly caused by the early start of crop growth and was partly a characteristic of the model, and started latest in the AFRCWHEAT run because of the late start of crop growth.

The simulations of water-limited wheat growth in Sevilla were repeated for a second year (validation). TB was 1 to 2 tons higher than TB in the first year, with the highest value again in the NWHEAT run and the lowest in the AFRCWHEAT run. The time course of TB in the different model runs was similar, except that in the CERES and SIRIUS runs crop growth started more rapidly in spring than in the other two model runs. Near maturity growth stopped at a relatively early date in the AFRCWHEAT run, probably because of water shortage, and at a relatively late date in the NWHEAT run. SIRIUS again calculated a relatively small increase in TB during the main growth period. The courses of LAI were about the same as those simulated for the other site and year. For ET and NB the same applied as described for the first run in Sevilla.

In Rothamsted, increasing temperature resulted in a continuous decrease in TB and GR. These decreases were approximately the same in the different model runs except for a stronger decrease in TB in the SIRIUS run. Absolute values for TB and GR, however, were considerably different. CV of grain yield did not change with increasing temperature and was about the same in most model runs. Only if water supply became more limiting was a higher value for CV calculated. ET increased with rising temperature in the SIRIUS run, remained the same in the AFRCWHEAT run and decreased in the CERES and NWHEAT runs. ET was highest in the NWHEAT and SIRIUS runs.

In Sevilla, increasing temperature also resulted in a continuous decrease in TB and GR. These decreases varied moderately between the different model runs, but the absolute values for TB and GR were considerably different. In runs with a severely limiting water supply, decreasing temperature and the resulting longer growth period also resulted in a decrease in TB and GR. CV of grain yield changed in the same way as described for Rothamsted. ET decreased with rising temperature in the CERES and NWHEAT potential production runs and decreased slightly or remained almost constant in the water-limited runs. ET was highest in the CERES runs, which was different from ET in runs for Rothamsted.

In Rothamsted, increasing rainfall resulted in a continuous increase in TB, GR and ET and in a decrease in CV of grain yield. In the NWHEAT water-limited run, the effects of increasing rainfall were much stronger than in the other model runs, indicative of a much more limited water supply. In Sevilla, increasing rainfall resulted in the same changes as found at Rothamsted. In most model runs increasing rainfall gave rise to strong changes, except for the AFRCWHEAT run where water supply appeared to be almost non-limiting.

In Rothamsted, CO_2 enrichment resulted in approximately the same increases in TB and GR in the different model runs. This CO_2 effect on yield was curvilinear in the NWHEAT runs and linear in the other runs, but for the CO_2 range used in the scenario runs this difference did not result in a considerably different effect of increased CO_2. In general, CV of grain yield did not change with increasing atmospheric CO_2 concentration, except in the NWHEAT water-limited run where CV decreased with increasing CO_2 because the water supply became less limiting for crop growth. ET increased slightly with increasing CO_2 in the AFRCWHEAT and SIRIUS runs as a result of the increasing leaf area and decreased slightly and considerably in the NWHEAT and CERES runs, respectively, because of the decrease in stomatal conductance. In Sevilla, the effect of increasing CO_2 on TB, GR and CV of grain yield was about the same as that observed for Rothamsted, except that larger CO_2 effects on TB and GR occurred in the NWHEAT run. ET did not change with increasing CO_2 in the AFRCWHEAT and SIRIUS runs and slightly decreased in the CERES and NWHEAT runs.

The effect of changes in climatic variability on the models was also examined. A doubling of daily temperature variability at Rothamsted had little effect on TB and GR in the AFRCWHEAT and SIRIUS runs, but they became slightly and considerably less in the SOILN and the CERES and NWHEAT runs respectively. Doubled temperature variability in Sevilla did not affect TB and GR in the SIRIUS run, but it considerably reduced TB and GR in the AFRCWHEAT, CERES and NWHEAT runs. CV of grain yield slightly increased with a doubling of temperature variability in all runs for both sites. Doubling the length of dry spells in the climate data set for Rothamsted gave identical values for TB, GR and ET in the SIRIUS run and slightly smaller values in the AFRCWHEAT, CERES and NWHEAT water-limited runs. CV of grain yield increased slightly by doubling of dry spells in the AFRCWHEAT, SIRIUS and CERES water-limited runs and increased more strongly in the NWHEAT water-limited run, indicative of a stronger yield-reducing effect of water shortage in this run. Doubling of dry spells in Sevilla resulted in lower values for TB, much lower values for GR and ET and much higher values for CV of grain yield in the CERES, NWHEAT and SIRIUS runs, but in no change in TB, GR and CV of grain yield in the AFRCWHEAT run. This can largely be explained by the amount of precipitation, which was approximately halved by doubling of dry spells. Only in the

AFRCWHEAT model was the soil water supply large enough to compensate for this effect.

Simulations of crop growth have been conducted for a number of different scenario climates, derived from transient GCM experiments, i.e. UKTR and GFDL scenarios, and from equilibrium GCM experiments, i.e. UKLO and UKHI scenarios. On the basis of the UKTR and UKHI climate scenarios, scenarios with the same monthly mean changes in variables but with changed temperature variability and length of dry spells have been constructed, i.e. UKTR6675V and UKHIV. An increased level of atmospheric CO_2 that corresponded with the scenario climate change, was taken into account in most simulations. As a higher atmospheric CO_2 concentration resulted in an considerable increase in CO_2 assimilation rate and in a slight decrease in transpiration in most model runs, the impact of climate change was first analysed independent of the direct effect of increased CO_2. This was done for the UKTR scenario at Rothamsted.

In Rothamsted, the UKTR6675 scenario, without the direct effect of increased atmospheric CO_2, resulted in a slight decrease in GR in the potential production runs, compared to GR at present. This can be explained by the shorter growth duration as a result of the higher temperatures in this scenario climate. With changed climatic variability in the UKTR6675V scenario, GR did not change in the potential runs. However, although a change in temperature variability had no effect on crop phenology and growth according to the different models, this may not be true in practice (J.R. Porter, pers. comm., 1995). For the UKTR3140 scenario climate, lower GR was calculated than GR at present and in the UKTR6675 scenario climate. This difference can be explained by the lower amount of irradiation in the UKTR3140 scenario climate. There was virtually no change in the CV of grain yield with climate change on the basis of the UKTR3140 and UKTR6675 scenarios. Only changed climatic variability (UKTR6675V) gave a slightly higher value for CV and SOILN calculated an increase in CV for the UKTR3140 scenario.

In the water-limited runs for Rothamsted, the UKTR6675 scenario resulted in no change in GR and the UKTR3140 scenario resulted in both higher and lower values for GR, compared to GR at present. With changed climatic variability in the UKTR6675V scenario, GR in the SIRIUS run remained almost the same and decreased slightly in the CERES and AFRCWHEAT runs and strongly in the NWHEAT run. CV of grain yield was approximately the same for both present and UKTR3140 and UKTR6675 scenario climates and was slightly higher with changed climatic variability (UKTR6675V) in most runs. This indicated that the degree of growth reduction caused by water shortage changed very little with climate change. The NWHEAT water-limited runs resulted in relatively high values for CV, both for present and scenario conditions, which indicated the larger risk for yield reduction by water shortage in this model run.

The UKTR6675 scenario for Rothamsted, including the direct effect of increased atmospheric CO_2, resulted in a considerable increase in GR in the potential runs. Changed climatic variability in the UKTR6675V scenario did not change GR in the different runs, as found for the present CO_2 runs. These results were also found for Sevilla, except that the increase in GR was quite small. For the UKTR3140 scenario, GR in Rothamsted was similar or slightly smaller than GR at present. The positive effect on crop growth of CO_2 enrichment was almost counter balanced by the relatively low irradiation in this scenario climate. In Sevilla irradiation was probably less limiting and, hence, similar or slightly higher GR was calculated for the UKTR3140 scenario. CV of grain yield in both Rothamsted and Sevilla did not change in the potential runs for the UKTR scenarios.

In the water-limited runs for Rothamsted, the UKTR6675 scenario resulted in a considerable increase in GR. This was a result of the higher CO_2 concentration. For Sevilla considerable increases were also calculated in the NWHEAT and SIRIUS runs, but in the AFRCWHEAT and CERES runs increases in GR were nil to slight. With changed climatic variability (UKTR6675V), GR at Rothamsted remained almost the same in the SIRIUS and CERES runs and considerably decreased in the NWHEAT and AFRCWHEAT runs, but at Sevilla strong decreases occurred in all runs except for the AFRCWHEAT run where GR remained constant.

These changes in GR depended mainly on the change in the risk of water shortage. A more detailed analysis of the consequences of changed climatic variability (UKTR6675V) in Sevilla showed that the distribution of GR was split with approximately a 50% probability of very low GR and a 50% probability of GR comparable with GR for the UKTR6675 scenario. This illustrated that wheat production may become a risky agricultural activity as a result of climate change, and that the incorporation of climatic variability into climate change scenarios may change the conclusions concerning the future suitability of wheat production in Sevilla. CV of grain yield in Rothamsted was low and did not change with climate change in the SIRIUS and CERES runs. This indicated that water supply was not limiting for crop growth. In the AFRCWHEAT run CV of grain yield was slightly higher and in the NWHEAT run much higher than in the CERES and SIRIUS runs, with the lowest value for CV for the UKTR3140 scenario and the highest values for the present climate and the UKTR6675V scenario. This indicated the relatively high risk for yield reduction by water shortage in the NWHEAT run, in particular, at present or in the UKTR6675V scenario climate. In Sevilla CV of grain yield was low for both present and UKTR scenario conditions in the CERES and AFRCWHEAT runs. In the SIRIUS and NWHEAT runs, CV was low in the UKTR6675 scenario climate and considerably higher for the present and UKTR3140 scenario climate. Changed climatic variability in the UKTR6675V scenario resulted in very high values for CV in all model runs except that of AFRCWHEAT.

The transient scenarios were constructed using the same global mean temperature change and concentration of atmospheric CO_2 and, hence, are directly comparable. In the potential runs for Rothamsted, the GFDL2534 scenario gave a slight decrease in GR and the GFDL5564 scenario resulted in a moderate increase in GR. This was fairly similar to results from both model decades of the UKTR GCM. The decrease in GR in the first decade was caused by the relatively low amount of irradiation and the increase in GR in the second decade was mainly caused by the increase in atmospheric CO_2. It was remarkable that at Rothamsted the scenarios for the first decade from both transient GCM experiments had a considerably lower level of irradiation than both the level at present and that in the scenario for the second decade. In Sevilla, the GFDL scenario for both decades resulted in slight to moderate increases in GR and the UKTR scenarios in nil to slight increases for the first decade and slight to moderate increases for the second decade. In Sevilla the amount of irradiation in the first decade was less limiting than in Rothamsted which resulted in more positive yield changes. CV of grain yield was rather low in the potential runs and virtually did not change for the GFDL scenarios for both decades. This corresponds with the CV of grain yield determined for the UKTR scenarios.

In the water-limited runs the GFDL2534 scenario gave a slight decrease in GR in the SIRIUS run and slight to moderate increases in the NWHEAT and AFRCWHEAT runs for Rothamsted and nil to slight increases in all runs for Sevilla. If water supply was not limiting, the low amount of irradiation in the first decade resulted in lower GR at Rothamsted. The increase in rainfall and the decrease in potential ET for this decade resulted in higher GR if water supply was currently limiting. For Sevilla the amount of rainfall in the GFDL2534 scenario was less than that at present. This resulted in no change in GR if water supply was limiting (e.g. NWHEAT) and slight increases in the other model runs with a larger water supply. The GFDL5564 scenario gave a considerable increase in GR at Rothamsted and a slight to moderate increase at Sevilla. This was mainly the result of the increase in atmospheric CO_2 which resulted in a higher growth rate and water use efficiency. In Sevilla the positive effect of climate change appeared to be less than in Rothamsted. This can be explained from the increase in temperature which resulted in a considerable decrease in GR at Rothamsted, but in a very strong decrease at Sevilla where temperatures are currently much higher (see Sections 5.7.5.1 and 5.7.5.3). These GFDL results were similar to those for the UKTR scenario in comparable decades. CV of grain yield was low in the CERES and SIRIUS runs for Rothamsted and changed very little with climate change on the basis of both UKTR and GFDL experiments. This indicated that water supply was not limiting in these model runs. In Sevilla the same applied for the CERES and AFRCWHEAT runs. CV of grain yield in Rothamsted was generally slightly higher in the AFRCWHEAT run and much higher in the NWHEAT run. In both model runs CV was generally lower for GFDL and UKTR scenario climates than for the present climate. For both scenarios the lower value for CV was caused by increased rainfall and/or decreased potential ET, compared to present conditions. In Sevilla CV of grain yield was relatively high in the SIRIUS and NWHEAT runs for both present and scenario climates with the highest value for CV calculated for the first decade of both GFDL and UKTR scenarios.

The effects of climate change were also analysed using scenarios based on output from equilibrium $2xCO_2$ GCM experiments. When comparing results for these UKLO and UKHI scenarios, it should be taken into account that both the distribution of climate change over Europe and the global mean temperature changes are different. Higher temperature changes are generally predicted in the UKLO, compared to the UKHI, scenario. For example, in Rothamsted the UKLO scenario gave a temperature rise of 6.6°C averaged over the year and the UKHI scenario a mean temperature rise of about 5.8°C. Further, comparing results from these equlibrium scenarios with those from the transient UKTR6675 scenario the following differences should be considered: (i) they have different distributions of climate change over Europe; (ii) they are standardised on different global mean temperatures (much smaller temperature changes are predicted in the UKTR6675 scenario, eg. 2.7°C averaged over the year for Rothamsted); and (iii) the CO_2 concentration for the equilibrium scenarios is 560 ppmv and for the UKTR6675 scenario is 617 ppmv.

In the potential runs GR at Rothamsted decreased nil to slightly and nil to moderately for UKHI and UKLO scenarios, respectively, and nil to slightly for both scenarios in Sevilla. Compared to the changes in GR for the UKTR6675 scenario which were considerably positive at Rothamsted and slightly to moderately positive at Sevilla, the effects of the UKLO and UKHI scenarios on GR were very small or even negative. This was partly the result of the smaller increase in atmospheric CO_2 in the UKLO and UKHI scenarios and partly because of the larger temperature rise in these scenarios. CV of grain yield in Rothamsted and Sevilla increased nil to slightly for the UKLO and UKHI scenarios compared to CV at present, which was almost identical to the change in CV found for the UKTR6675 scenario.

In the water-limited runs for Rothamsted, both the UKLO and UKHI scenarios gave decreases in GR in the SIRIUS run and nil and moderate increases, respectively, in the other runs. For Sevilla the UKLO and UKHI scenarios gave nil to slight and moderate to strong decreases in GR respectively. GR at Sevilla for the UKHI scenario was much lower than GR for the UKLO scenario because the amount of rainfall was very low. Compared to the changes in GR for the UKTR6675 scenario which were considerably and slightly to considerably positive at Rothamsted and Sevilla respectively, the effects of the UKLO and UKHI scenarios on GR were small or negative. This was the result of the smaller increase in atmospheric CO_2 in the UKLO and UKHI scenarios, the larger temperature rise and the lower amount of rainfall in these scenarios. CV of grain yield at Rothamsted and Sevilla for the UKLO and UKHI scenarios was similar to CV at present. Exceptions were the NWHEAT run for Rothamsted where CV at present was much higher than CV for the scenarios, and the SIRIUS and NWHEAT runs for the UKHI scenario at Sevilla with a slightly and much higher CV respectively than CV at present. Furthermore, for the UKTR6675 scenario CV of grain yield was the same as CV at present in most runs except for the NWHEAT run at Rothamsted and the SIRIUS and NWHEAT runs at Sevilla which experienced a relatively higher CV than at present.

5.7.8 Conclusions

Total biomass and grain yield were simulated reasonably well by the different models. Even when simulated growth in spring started too early and too fast, a good yield prediction was still possible. The course of leaf area index was not simulated well by most models. Fortunately, dry matter production is not much different for leaf area index values varying between 4 and 10. The courses of leaf area index as calculated for both sites differed only slightly and appeared to be rather characteristic for each model.

Cumulative evapotranspiration was simulated quite accurately by the different models. Differences in evapotranspiration were often caused by the amount of available water and that mainly depended on the assumed soil water storage. Models that overestimated the leaf area index in early spring also overestimated evapotranspiration during this period. The nitrogen uptake by the crop was also simulated quite well by the different models, although the simulated time course was not always the same as the observed. Differences in nitrogen uptake were caused mainly by the amount of mineral nitrogen in the rooted soil profile and its availability for crop uptake. These factors generally limited nitrogen uptake at the end of the growth period.

A broad survey of the sensitivity of grain yield to changes in mean climatic variables, climatic variability and atmospheric CO_2 concentration and to changes in climate as based on equilibrium and transient scenarios is given in Table 5.7.5. These results are based on simulation runs with the different wheat models.

Increasing temperature resulted in a continuous decrease in total biomass and grain yield in the different model runs. If the water supply was severely limiting, an opposite temperature effect occurred. The CV of grain yield did not change with increasing temperature, however cumulative evapotranspiration increased, remained the same or decreased depending on the model.

Increasing rainfall resulted in a continuous increase in total biomass, grain yield and cumulative evapotranspiration, and in a decrease in CV of grain yield. This rainfall effect was found in all model runs and became stronger if water supply was more limiting.

Increasing atmospheric CO_2 resulted in similar increases in total biomass and grain yield and in no change in CV of grain yield in the different model runs. CV of grain yield only decreased if increased CO_2 led to less water limitation. Cumulative evapotranspiration increased or decreased with increasing CO_2 depending on the model.

In the sensitivity analyses the various models calculated considerably different values for cumulative evapotranspiration. These differences in value between model runs for Rothamsted clearly differed from the differences in value between model runs for Sevilla.

By doubling the variability in the temperature data, total biomass and grain yield remained the same or became considerably less, depending on the model and CV of grain yield slightly to moderately increased. Doubling the length of dry spells resulted in smaller values for total biomass, grain yield and evapotranspiration and higher values for CV of grain yield. However, this effect was mainly caused by the decrease in amount of rainfall and only to a limited extent by the change in rainfall distribution.

The UKTR6675 scenario of climate change resulted in considerable increases in grain yield in Rothamsted and in nil to considerable increases in Sevilla for both potential and water-limited runs. This scenario resulted in the same value for CV of grain yield in the potential runs for both sites and in the same or lower value for CV of grain yield in the water-limited runs. Changed climatic variability in UKTR6675V did not change grain yield in the potential runs, but resulted in nil to considerable decreases in water-limited runs for Rothamsted depending on the model and in strong decreases in most water-limited runs for Sevilla. CV of grain yield strongly increased with changed climatic variability in situations with water shortage, in particular, the water-limited runs for Sevilla.

If the direct effect of increased atmospheric CO_2 was not taken into account, the UKTR6675 scenario alone for Rothamsted resulted in a slight decrease in grain yield in potential runs and in no change in grain yield in water-limited runs. This scenario resulted in the same or slightly lower values for CV of grain yield in all runs. The direct effect of increased atmospheric CO_2 on grain yield was strongly positive compared to the effect of the predicted changes in climate. CV of grain yield decreased only with increasing CO_2 if simultaneously water shortage decreased.

The GFDL5564 scenario resulted in moderate and slight to moderate increases in grain yield in the potential runs for Rothamsted and Sevilla respectively and in considerable and slight to moderate increases in grain yield in the water-limited runs for Rothamsted and Sevilla respectively. This scenario resulted in a constant CV of grain yield in the potential runs for Rothamsted and Sevilla and the same or lower value for CV in the water-limited runs. Comparing results from the UKTR and GFDL scenarios, these scenarios resulted in almost the same change in grain yield and in CV of grain yield.

The scenarios for the first decade from both the GFDL and UKTR experiments had a considerably lower level of irradiation, in particular for Rothamsted, than the level at present and that in the scenario for the second decade. This resulted in decreases or relatively small increases in yield.

The UKLO and UKHI scenarios resulted in nil to moderate decreases in grain yield in the potential runs and from considerable decreases to moderate increases in grain yield in the water-limited runs. The amount of rainfall in the UKHI scenario for Sevilla was very low and resulted in low yields in most water-limited runs. Compared to the changes in grain yield for the UKTR6675 scenario, the effects of the UKLO and UKHI scenarios on grain yield were small or even negative. These scenarios resulted in a nil to slight increase in CV of grain yield in the potential runs for both Rothamsted and Sevilla and in no change in CV of grain yield in most water-limited runs. Such changes in CV of grain yield were similar to the changes calculated for the UKTR6675 scenario.

Comparison of the distribution of grain yields in Sevilla for the UKTR6675 scenarios with and without changed climatic variability showed that incorporation of climatic variability into climate change scenarios may change the conclusions concerning the future suitability of wheat production at Sevilla. Changes in climatic variability may result in both a lower mean grain yield and a larger yield variation and, thus, a greater risk of very low yields.

For most climate change scenarios the simulation models gave a range of results on grain yield and CV of grain yield that were not too widely apart. If results from the various models were very different, a considerable element of the differences could often be explained on the basis of model sensitivity and input data. Although the models have been calibrated on the same data sets, it became clear from this analysis that there were still differences in input data, for example, the initial and maximum amount of available soil water. This resulted in large differences in model results in growth periods with a low amount of rainfall.

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5.8 Effects on cereal weeds

5.8.1 Background

Cropping systems are influenced by the distribution and abundance of weeds. Crop-weed interactions may alter with changes in climate and atmospheric conditions. Current simulation models of crop growth and development do not usually account for competition from weeds.

Avena sterilis is a weed of international importance. It can cause considerable losses of yield in winter cereals, and requires costly methods of chemical and cultural control (Holm *et. al.*, 1977). *A. sterilis* occurs in regions with warm and dry climates, predominately in all Mediterranean countries as well as in eastern Australia (Fernandez-Quintanilla *et. al.*, 1987). The geographical distribution of *A. sterilis* is related to its temperature and water requirements for germination and emergence.

Table 5.7.5 Summary table of the sensitivity[1] of grain yield to changes in mean climate variables, climatic variability and atmopheric CO_2 concentration and to changes in climate based on the equilibrium and transient scenarios, both with and without changes in climatic variability. Results are based on simulation runs with the different models for both potential (+I) and water-limited production (-I) at Rothamsted, U.K. and Sevilla, Spain.

	AFRCWHEAT	CERES		NWHEAT		SIRIUS	SOILN
	-I	+I	-I	+I	-I	-I	+I
Rothamsted							
Sensitivity to							
- temperature	- (+)[2]	-	-	- (+)[2]	- (+)[2]	-	-
- precipitation	+	0	+	0	+	+	0
- atmospheric CO_2	+	+	+	+	+	+	+
- doubled variability in temperature	0	-	-	-	-	0	-
- doubled length of dry spells	0	0	0	0	0	0	0
Scenarios[3]							
- UKLO	0	0	0	-	0	-	-
- UKHI	+	0	+	-	+	-	-
- UKHIV	+	0	0	-	0	0	-
- UKTR3140	+	0	0	0	+	0	-
- UKTR6675*	0	0	0	-	0	0	-
- UKTR6675	+	+	+	+	+	+	+
- UKTR6675V	0	+	+	0	0	+	+
- GFDL2534	0	?	?	-	+	-	?
- GFDL5564	+	+	+	+	+	+	?
Sevilla							
Sensitivity to							
- temperature	-	-	- (+)[2]	-	- (+)[2]	-/+	?
- precipitation	0	0	+	0	+	+	?
- atmospheric CO_2	+	+	+	+	+	+	?
- doubled variability in temperature	-	-	-	-	-	0	?
- doubled length of dry spells	0	0	-	0	-	-	?
Scenarios[3]							
- UKLO	-	0	+	-	0	0	?
- UKHI	-	?	?	-	-	-	?
- UKHIV	-	?	?	-	-	-	?
- UKTR3140	0	0	0	+	0	0	?
- UKTR6675	0	+	+	+	+	+	?
- UKTR6675V	0	+	-	+	-	-	?
- GFDL2534	+	?	?	+	0	0	?
- GFDL5564	+	0	+	+	+	+	?

1 + / 0 / - : positive / nil / negative effect of increase in temperature etc. on grain yield. ? : no simulation result.

2 positive effect at low temperatures.

3 for information on the scenarios see section 5.7.6 . Simulations were done for scenario climate with the corresponding increased level of atmospheric CO_2, except for the UKTR6675* scenario which assumed ambient CO_2 (353 ppmv).